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16. ABSTRACT

This study assesses the likelihood of new process technology and new practices being introduced by energy intensive industries and explores the environmental impacts of such changes.

Specifically, Vol. III deals with the iron and steel industry and examines four alternatives: (1) recovery of carbon monoxide from BOP (basic oxygen process), (2) external desulfurization of blast-furnace hot metal, (3) conversion from wet to dry coke quenching, and (4) direct reduction of iron ore, all in terms of relative process economics and environmental/energy consequences. Vol. IV-XV deal with the following industries: petroleum refining, pulp and paper, olefins, ammonia, aluminum, textiles, cement, glass, chlor-alkali, phosphorus and phosphoric acid, copper, and fertilizers. Vol. I presents the overall summation and identification of research needs and areas of highest overall priority. Vol. II, prepared early in the study, presents and describes the overview of the industries considered and presents the methodology used to select industries.

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EPA-600/7-76-034c
December 1976

ENVIRONMENTAL CONSIDERATIONS OF SELECTED ENERGY CONSERVING MANUFACTURING PROCESS OPTIONS

Volume III

IRON AND STEEL INDUSTRY REPORT

EPA Contract No. 68-03-2198

Project Officer

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory - Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This study, consisting of 15 reports, identifies promising industrial processes and practices in 13 energy-intensive industries which, if implemented over the coming 10 to 15 years, could result in more effective utilization of energy resources. The study was carried out to assess the potential environmental/energy impacts of such changes and the adequacy of existing control technology in order to identify potential conflicts with environmental regulations and to alert the Agency to areas where its activities and policies could influence the future choice of alternatives. The results will be used by the EPA's Office of Research and Development to define those areas where existing pollution control technology suffices, where current and anticipated programs adequately address the areas identified by the contractor, and where selected program reorientation seems necessary. Specific data will also be of considerable value to individual researchers as industry background and in decision-making concerning project selection and direction. The Power Technology and Conservation Branch of the Energy Systems-Environmental Control Division should be contacted for additional information on the program.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

EXECUTIVE SUMMARY

In 1973, the energy consumption in the iron and steel industry accounted for 6% of the national total and 17% of the total industrial sector. The total capacity of the industry is expected to grow at about 2.5% a year during the next 15 years.

It is in the manufacture of liquid steel that one finds the main areas where tradeoffs can be considered between energy conservation and pollution abatement. We selected four process options for study:

- Recovery of carbon monoxide from BOP (Basic Oxygen Process for steelmaking) vessels;
- External desulfurization of blast furnace hot metal;
- Conversion from the wet to the dry process for quenching of coke; and
- Direct reduction of iron ore.

The recovery of carbon monoxide from the BOP vessels provides the steelmaker with a new fuel source that can supplement other gaseous fuels throughout the steel plant. The value of the fuel can make this option economically attractive. Moreover better efficiency in gas cleaning also tends to favor this route. The industry is expected to adopt it widely in new facilities during the next 15 years.

External desulfurization provides the steelmaker with a way to use higher sulfur coke in the blast furnace or alternatively to reduce the coke rate and limestone consumption in the blast furnace. Fugitive, air and water pollution streams are created which are, however, similar in nature to others found in steelmaking. They will add only a small amount to the overall pollution load and can be easily controlled with existing technology. A preliminary economic analysis shows this option to be economically attractive when sulfur levels in the coke exceed about 1.2%. Some steelmakers are expected to build external desulfurization stations as a hedge against fluctuating prices and availability of low sulfur metallurgical coal. The iron and steel industry is expected to adopt this new option during the next 15 years although there appears to be question on the availability of desulfurizing reagents.

Dry quenching of coke is essentially an energy-saving option. It may be less polluting than wet quenching, although more research is needed for an accurate assessment. Prohibitively high capital investments do not make this option economically attractive when the recovered energy is credited on an oil equivalent basis. Only large integrated plants are expected to consider this option in the future in the face of changing economic conditions such as higher energy costs or newer technology reducing dry quenching investment requirements.

The subject of direct reduction of iron ore is a very complex one. The most proven commercial processes use gaseous reductants and are based on reformed natural gas or other petroleum derivatives. Gasified coal can also be used but so far this has not proved to be economically viable. The last major remaining alternative is the direct use of coal in a rotary kiln which was investigated in this study. The rotary kiln-electric furnace route is more energy consuming than the conventional coke oven-blast furnace-BOP route, but the former allows for the potential use of lower valued coals rather than premium metallurgical coals or gaseous fuels. It also eliminates the need for a major pollution source: the coke oven. However, it is not yet technically proven and is not expected to be widely practiced during the next 15 years in the United States.

This report was submitted in partial fulfillment of contract 68-03-2198 by Arthur D. Little, Inc. under sponsorship of the U.S. Environmental Protection Agency. This report covers a period from June 9, 1975 to January 30, 1976.

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During the course of the study we also had occasion to contact many individuals within industry and trade associations. Where appropriate we have made reference to these contacts within the various reports. Frequently, however, because of the study's emphasis on future developments with comparative assessments of new technology, information given to us was of a confidential nature or was supplied to us with the understanding that it was not to be credited. Therefore, we extend a general thanks to all those whose comments were valuable to us for their interest in and contribution to this study.

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ENGLISH-METRIC (SI) CONVERSION FACTORS

To Convert From	To	Multiply By
Acre	Metre^2	4,046
Atmosphere (normal)	Pascal	101,325
Barrel (42 gal)	Metre^3	0.1589
British Thermal Unit	Joule	1,055
Centipoise	Pascal-second	0.001
Degree Fahrenheit	Degree Celsius	$t^{\circ}_{C} = (t^{\circ}_{F} - 32)/1.8$
Degree Rankine	Degree Kelvin	$t^{\circ}_{K} = t^{\circ}_{R}/1.8$
Foot	Metre	0.3048
Foot^3/minute	Metre^3/sec	0.0004719
Foot^3	Metre^3	0.02831
Foot^2	Metre^2	0.09290
Foot/sec	Metre/sec	0.3048
Foot^2/hr	Metre^2/sec	0.00002580
Gallon (U.S. liquid)	Metre^3	0.003785
Horsepower (550 ft-lbf/sec)	Watt	745.7
Horsepower (electric)	Watt	746.0
Horsepower (metric)	Watt	735.5
Inch	Metre	0.02540
Kilowatt-hour	Joule	3.60×10^{6}
Litre	Metre^3	1.000×10^{-3}
Micron	Metre	1.000×10^{-6}
Mil	Metre	0.00002540
Mile (U.S. statute)	Metre	1,609
Poise	Pascal-second	0.1000
Pound force (avdp)	Newton	4.448
Pound mass (avdp)	Kilogram	0.4536
Ton (assay)	Kilogram	0.02916
Ton (long)	Kilogram	1,016
Ton (metric)	Kilogram	1,000
Ton (short)	Kilogram	907.1
Tonne	Kilogram	1,000

Source: American National Standards Institute, "Standard Metric Practice Guide," March 15, 1973. (ANS72101-1973) (ASTM Designation E380-72)

I. INTRODUCTION

A. BACKGROUND

Industry in the United States purchases about 27 quads* per year, approximately 40% of the total national energy usage.** This energy is used for chemical processing, raising steam, drying, space cooling and heating, process stream heating, and miscellaneous other purposes.

In many industrial sectors energy consumption can be reduced significantly by better "housekeeping" (i.e., shutting off standby furnaces, better thermostat control, elimination of steam and heat leaks, etc.) and greater emphasis on optimization of energy usage. In addition, however, industry can be expected to introduce new industrial practices or processes either to conserve energy or to take advantage of a more readily available or less costly fuel. Such changes in industrial practices may result in changes in air, water or solid waste discharges. The EPA is interested in identifying the pollution loads of such new energy-conserving industrial practices or processes and in determining where additional research, development, or demonstration is needed to characterize and control the effluent streams.

B. CRITERIA FOR INDUSTRY SELECTION

In the first phase of this study we identified industry sectors that have a potential for change, emphasizing those changes which have an environmental/energy impact. Industries were eliminated from further consideration if the only process changes that could be envisioned were:

- energy conservation as a result of better policing or "housekeeping,"
- better waste heat utilization,
- fuel switching in steam raising, or
- power generation.

After discussions with the EPA Project Officer and his advisors, industry sectors were selected for further consideration and ranked according to:

---

*Quad = 10^{15} Btu.

**Purchased electricity valued at an approximate fossil fuel equivalence of 10,500 Btu/kWh.

- **Quantitative** criteria based on the gross amount of energy (fossil fuel and electric) purchased by industry sectors, as shown in U.S. Census figures and from information provided from industry sources: the iron and steel industry purchased 3.49 quads of the 12.14 quads purchased in 1971 by the 13 industries selected for study, or 13% of the 27 quads purchased by all industry (see Table I-1).
- **Qualitative** criteria relating to probability and potential for process change, and the energy and effluent consequences of such changes.

In order to allow for as broad a coverage of technologies as possible, we then reviewed the ranking, eliminating some industries in which the process changes to be studied were similar to those in another industry planned for study. We believe the final ranking resulting from these considerations identifies those industry sectors which show the greatest possibility of energy conservation via process change. Further details on this selection process can be found in the Industry Priority Report prepared under this contract (Volume II).

Among the 13 industrial sectors listed, the iron and steel industry appeared in first place.

TABLE I-1

SUMMARY OF ENERGY PURCHASED IN SELECTED INDUSTRY SECTORS, 1971

	Industry Sector	10^{15} Btu/Yr.	SIC Code In Which Industry Found
1.	Blast furnaces and steel mills	3.49(1)	3312
2.	Petroleum refining	2.96(2)	2911
3.	Paper and allied products	1.59	26
4.	Olefins	0.984(3)	2818
5.	Ammonia	0.63(4)	287
6.	Aluminum	0.59	3334
7.	Textiles	0.54	22
8.	Cement	0.52	3241
9.	Glass	0.31	3211, 3221, 3229
10.	Alkalies and chlorine	0.24	2812
11.	Phosphorus and phosphoric acid production	0.12(5)	2819
12.	Primary copper	0.081	3331
13.	Fertilizers (excluding ammonia)	0.078	287

(1) Estimate for 1967 reported by FEA Project Independence Blueprint, p. 6-2, USGPO, November 1974.

(2) Includes captive consumption of energy from process byproducts (FEA Project Independence Blueprint)

(3) Olefins only, includes energy of feedstocks: ADL estimates

(4) Amonia feedstock energy included: ADL estimates

(5) ADL estimates

Source: 1972 Census of Manufactures, FEA Project Independence Blueprint, USGPO, November 1974, and ADL estimates.

C. CRITERIA FOR PROCESS SELECTION

In this study, we focused on identifying changes in the primary production processes which have clearly defined pollution consequences. In selecting those to be included in this study, we considered the needs and limitations of the EPA as discussed more completely in the previously mentioned Industry Priority Report. Specifically, energy conservation is broadly defined to include, in addition to process changes, conservation of energy or energy form (gas, oil, coal) by a process or feedstock change. Natural gas has been considered as having the highest form value of energy, followed in descending order by oil, electric power, and coal. Thus, a switch from gas to electric power would be considered energy conservation because electric power could be generated from coal, whose reserves in the United States, in comparison to natural gas, are abundant. Moreover, pollution control methods resulting in energy conservation have been included within the scope of this study. Finally, emphasis was placed on process changes with near-term rather than long-term potential within the 15-year span of time of this study.

In addition to excluding from consideration better waste heat utilization, "housekeeping," power generation, and fuel switching, as mentioned above, certain other options were excluded to avoid duplication of work being funded under other contracts and to focus this study more strictly on "process changes." Consequently, the following have also not been considered to be within the scope of work:

- Carbon monoxide boilers (however, unique process vent streams yielding recoverable energy could be mentioned);
- fuel substitution in fired process heaters;
- mining and milling, agriculture, and animal husbandry;
- substitution of scrap (such as iron, aluminum, glass, reclaimed textiles, and paper) for virgin materials;
- production of synthetic fuels from coal (low- and high-Btu gas, synthetic crude, synthetic fuel oil, etc.); and
- all aspects of industry-related transportation (such as transportation of raw materials).

D. SELECTION OF IRON AND STEEL INDUSTRY PROCESS OPTIONS

Within each industry the magnitude of energy use was an important criterion in judging where the most significant energy savings might be realized, since reduction of energy use reduces the amount of pollution generated in the energy production step. Guided by this consideration, candidate options for in-depth analysis were identified from the major energy-consuming process steps with known or potential environmental problems.

After developing a list of candidate process options, we assessed subjectively the:

- pollution or environmental consequences of the change,
- probability or potential for process change, and
- energy conservation consequences of the change.

Even though all of the candidate process options were large energy users, there was wide variation in energy use and estimated pollution loads between options at the top and bottom of the list. A modest process change in a major energy-consuming process step could have more dramatic consequences than a more technically significant process change in a process step whose energy consumption is rather modest. Process options were selected for in-depth analysis only if a high probability for process change and pollution consequences in the alternative process steps was perceived.

Because of time and scope limitations for this study, we have not attempted to prepare a comprehensive list of process options, or to consider all economic, technological, institutional, legal, or other factors affecting implementation of these changes. Instead, we have relied on our own background experience, industry contacts, and the guidance of the Project Officer and EPA advisors to choose 16 reasonably promising process options (with the emphasis on near-term potential) for analysis.

After discussion with the EPA Project Officer, his advisors, and industry representatives, we narrowed the list of candidates to four:

- Recovery of carbon monoxide from BOP (basic oxygen process) vessels,
- External desulfurization of blast-furnace hot metal,
- Conversion from wet to dry coke quenching, and
- Direct reduction of iron ore.

We discarded options, for example, if it appeared that:

- the technology seemed to have limited use in terms of the type of product produced and the expected production volume, or
- the practice of the technology implied a manifestly unattractive pattern of energy consumption.

Recognizing that capital investments and energy costs have escalated rapidly in the past few years and have greatly distorted the traditional basis for making cost comparisons, we developed costs representative of the first half of 1975 using constant 1975 dollars for our comparative analysis of new and current processes.

II. FINDINGS AND CONCLUSIONS

The main characteristics of the four options analyzed in depth are summarized in Table II-1.

A. RECOVERY OF CARBON MONOXIDE FROM BOP VESSELS

The basic oxygen process (BOP) off-gases consist largely of carbon monoxide and are thus highly combustible. In conventional practice, since there is no provision to prevent air from entering, these hot gases combust spontaneously in the gas-collecting hood.

Non-combustion systems prevent this air infiltration; they cool and clean the CO-rich gases without burning them and thus make them available as a gaseous fuel for general purpose.

Two U.S. firms--American Air Filter in Louisville, Kentucky and Chemico in New York City--offer engineered collection systems. The former offers a system based on a French process (IRSID-CAFL)* and the latter one is based on a Japanese process (OG).**

The main findings relating to carbon monoxide collection are:

- The recovered gas has a heating value of about 200 to 250 Btu/scf.*** This represents about 0.4 to 0.5 x 10^6 Btu per ton of raw steel.
- In recent years more than 100 CO collection installations have been, or are being, built largely in the United States, Europe and Japan. In the United States the gas recovered from 59 reported non-combustion systems (Stone 1976) is temporarily flared rather than utilized.
- The dust content in the CO collection system is less oxidized than in the conventional combustion system, contains a smaller percentage of submicron particles, and is easier to collect. Treatment of water used in scrubbing is facilitated because of the more rapid settling characteristics that result. Solid waste disposal methods are unaffected.

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*IRSID-CAFL - Institut de Recherche de la Siderurgie-Compagnie des Atelias et Forges de la Loire.

**OG = oxygen converter gas recovery process.

***scf = standard cubic foot.

TABLE II-1

SUMMARY OF COSTS/ENERGY/ENVIRONMENTAL ASPECTS
OF PROCESS OPTIONS IN THE IRON AND STEEL INDUSTRY

Process/ Factor	PROCESS OPTION Recovery of Carbon Monoxide from BOP Vessels	External Desulfurization of Blast-Furnace Hot-Metal	Conversion of Hot Coke Quenching from the Wet to the Dry Process	Direct Reduction
Environment	1) easier particulate collection 2) easier treatment of scrubber water 3) solid waste disposal unaffected	Virtually no change in steel plant overall emissions.	1) Eliminates emissions from the wet quenching process. 2) Additional potential for particulate emission, but control of such emissions is part of dry-quench design.	Absence of the coke ovens points toward significant reduction in pollutant emissions.
Pollution Control Costs				
Fixed Investment Operating Costs	\$ 4.40 vs \$ 2.70 \$ 0.66 vs \$ 1.12 per ton of steel	\$ 6.32 vs \$ 5.65 \$ 4.42 vs \$ 4.57 per ton of hot metal	N.S. N.S.	\$ 11.57 vs \$ 17.41 \$ 7.94 vs \$ 9.26 per ton of steel
Energy	Makes available 0.44 x 10^6 Btu/ton of steel in the form of a combustible gas. (220 Btu/Scf.)	Allows shift from low-sulfur to higher-sulfur metallurgical coal.	Energy credit from the partial recovery of the sensible heat of the incandescent coke. However, less breeze is made available for sintering, etc.	Less efficient process, but permits use of abundant non-metallurgical coal.
Economics	Necessity of a gas holder results in higher capital costs. Operating costs are lower because of energy credit.	Main capital expenditure is for pollution control equipment. Main operating expenditure is for the desulfurizing agent. Economically favored when the sulfur content of the coke is greater than 1.2%	Capital and operating costs significantly higher than for wet quenching.	Economics would favor DR mini-mills if the technology were reliable enough for the process to operate according to specifications.
Process Economics				
Fixed Investment Operating Costs	(see pollution control costs) (see pollution control costs)	N.S. N.S.	\$ 9.5 (incremental) \$ 1.18 (incremental) per ton of coke	\$ 151.92 vs \$ 135.09 \$ 147.83 vs \$ 143.40 per ton of steel

Remarks - Fixed investment costs are given in US dollars per annual ton of capacity
- Operating costs are given in US dollars per ton of product, including 20% pretax ROI.
- Costs are given as cost of option versus cost of base line, unless otherwise stated
- N.S. - Non Significative

- Compared with a total combustion system, the CO collection system with a gas holder will cost about 60% more in capital, mainly because of the need for a separate and independent hood and scrubber for each furnace.

- If the collected gas can be utilized and credited at $2/million Btu, the non-combustion collection system offers lower operating costs than the conventional BOP pollution control equipment.

- The cyclic pattern of generation, the need for a gas holder of several million cubic feet capacity or larger, the land needs associated with the gas holder, and the logistical problems in piping a collected gas to end-users combine to make industry regard this source of fuel gas as supplemental to its other fuel sources.

In view of these findings, the iron and steel industry is expected to implement non-combustion and recovery of the fuel value in BOP off-gases in the new installations built over the next 15 years. A large proportion of the remaining open-hearth capacity will be replaced by BOP, and the total capacity of the industry will increase at an average rate of about 2.5%/yr. Thus, by 1990 industry BOP capacity may be expected to increase 80-100 million tons above the level in 1973. A significant fraction of such capacity can be expected to be achieved by "rounding out" (i.e., capacity increases achieved by going from a two-vessel to a three-vessel BOP shop). Logistical factors, such as plant layout and existing facilities, are likely to have a major influence on the actual number of plants adopting the non-combustion recovery system.

B. EXTERNAL DESULFURIZATION OF HOT METAL

This additional step is an alternative method of controlling the sulfur content of blast furnace hot metal. In conventional practice, blast furnace sulfur content is completely controlled by adding limestone to form a sulfur bearing slag and by limiting the sulfur content of the metallurgical coke. External desulfurization is achieved by injecting sulfur retaining reagents (e.g., calcium or magnesium compounds in an inert gas such as nitrogen) into high sulfur hot metal from a blast furnace. These compounds form a sulfide slag that must be skimmed off prior to charging the hot metal into the BOP. Use of external desulfurization either permits limestone and coke rates to be reduced, or alternately allows the sulfur content in the coke to be increased without increasing the limestone charge to the blast furnace. An experimentation period to establish operating conditions specific to each plant seems appropriate, despite considerable experience with this practice overseas.

The main findings relating to external desulfurization follow:

- Fugitive, air, and water pollution problems are created. They are, however, similar in nature to other pollutants found in steelmaking. Moreover, they add only a small increment to the overall steelmaking pollution load and can be controlled with existing technologies.

- The sulfur content in finished steels, according to changing specifications, are decreasing slowly with time. Bulk contents ranging from 0.025-0.030% are common nowadays. This sulfur level depends on the amount of sulfur entering the blast furnace and on the fluxing practice adopted in running the blast furnace. An important decision parameter, therefore, is the quality of the coke (or coal) supply available to each plant. When the coke contains more than 1.2 - 1.5% sulfur, we believe that external desulfurization becomes economical.

- Aside from coke-rate implications, external desulfurization permits a better consistency to be obtained in the sulfur level of the hot metal charged to the BOP, thereby smoothing the steelmaking operation and increasing its yield.

- From an energy usage viewpoint, this option allows substitution of higher-sulfur metallurgical coal for less plentiful low-sulfur metallurgical coal, thus expanding the domestic reserves.

In view of these findings, several external desulfurization installations can be expected to be built during the next 15 years. The driving force is a gradual increase in the sulfur content of available metallurgical coals.

C. DRY COKE QUENCHING

This option is an alternative to wet quenching involving a water quench to cool the incandescent coke. In dry coke quenching, the coke is cooled by an inert gas stream. The sensible heat transferred to the inert gas can then be partially recovered for useful purposes.

The facilities involved in either method of quenching are physically separate from the coke ovens in that the incandescent coke is pushed from the oven and falls into a tracked car in which it is transported to the quenching area.

The main findings relating to dry quenching are:

- There are no such installations in the United States. Dry quenching of coke is practiced to some extent in the U.S.S.R. One company, the American Waagner Biro Company of Pittsburgh, designs and offers to install dry-quenching facilities through an associated engineering firm. Both the Russian design (offered by Licensintorg) and the Austrian design (American Waagner Biro) are based on an old Sulzer Bros. process (Hersche, 1946).

- There has been acceptance that when clean water is used in wet quenching the magnitude of the air emissions is significantly reduced, perhaps to the point where these can meet anticipated standards.

- According to Linsky (1975), dry quenching is claimed by Russian authors to produce a higher-grade coke, thus reducing the coke rate in the blast furnace. However, this claim needs to be demonstrated for U.S. coals. In addition, less production of coke breeze is claimed for dry quenching, thus increasing the coke yield. A research program would be appropriate to verify these claims. Thus the only demonstrated benefit of dry coke quenching to date is the significant amount of energy recoverable.

- The physical installation is more complex than that for wet quenching, and this complexity increases the capital cost significantly. The difference between a dry coke-quenching station with the associated tracked vehicle and a wet coke-quenching station is about $7 million for an annual production of 1 million tons of coke. Moreover, it appears that a standby coke-quenching station would have to be available to ensure reliable operations. This requirement could add another $2.5 million to the capital cost if the less costly wet quench unit is chosen as the standby unit. Only very large plants, using several quenching towers, could waive the requirement for a standby coke-quenching unit.

Therefore, the iron and steel industry probably will not adopt dry quenching of coke on any significant scale during the next 15 years. This situation could change if the economics of the process can be improved or it can be demonstrated that dry quenched coke measurably reduces blast furnace coke rates. Supporting experimental evidence so far is lacking.

D. DIRECT REDUCTION (DR)

New iron units (oxide pellets, lump ore, etc.) can be partially reduced in the solid state by reaction with a reducing gas mixture (CO and H_2) at temperatures ranging from 1470 to 2000°F. These prereduced materials are called sponge-iron or metallized materials, because up to 95% of their iron content is in the metallic state. They can partially or wholly replace purchased scrap in the steelmaking electric arc furnace. (The prereduced pellets may also be charged to the blast furnace to increase its productivity or be used in the oxygen steelmaking shop in lieu of scrap and as a cooling agent.) Many firms will design, engineer, and construct direct reduction plants; and interest in making steel by this route is intense worldwide.

The main findings related to direct reduction are:

- The most advanced direct reduction technology is based on the use of natural gas or a petroleum-based hydrocarbon as the energy source. Technology based on coal, employing the rotary kiln, is also available (SL/RN*, Krupp, etc.), but demonstration on an industrial scale for acceptance in the United States is still at least several years away. A successful large demonstration is vital for widespread application of this technology in the United States.

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*SL/RN = Stelco-Lurgi/Republic Steel, National Lead.

- The alternative use of coal for direct reduction purposes would be a gas-oriented process utilizing a coal gasification step to produce the necessary high-temperature reducing gases. Although the technological approaches are clear and research and development are active, commercial demonstration of this alternative lies further in the future because it has not proven economically attractive.

- The direct-reduction electric-furnace steelmaking route eliminates dependence on metallurgical coal, but consumes a larger quantity of energy per ton of steel than the blast furnace-coke oven-basic oxygen furnace route. Its energy conservation potential is one of form rather than quantity.

- Pollution control problems with the direct-reduction electric-furnace route are generally less severe than with the blast-furnace route. A major factor in this respect is the elimination of the need for coke ovens.

- The two routes (conventional coke oven-blast furnace-BOP vs. direct reduction-electric furnace) are about equally costly, in terms of both capital and operating expenses. Transportation costs and other site-specific economic conditions, together with reliability expectation differences, presently favor the traditional approach for the bulk of the steel industry. Because these total cost estimates are relatively small differences between large numbers, it will be worthwhile to re-examine this judgment periodically.

- The installation of a direct-reduction-electric furnace steelmaking sequence in the iron and steel plant may add flexibility in meeting changes in demand and decrease dependency on fluctuations in scrap prices.

- Certain locations in the world have the potential for low-cost manufacture of semi-finished products via direct reduction and electric furnace steelmaking, e.g., Venezuela with iron ore and surplus natural gas resources and the Middle East with surplus natural gas resources. Long-distance movement of metallized pellets, or even of semi-finished products in international trade, could become of major importance in facilities planning within the next 15 years.

- The use of partially metallized pellets in the electric furnace would produce a net increase in electricity consumption per ton of production as compared to all-scrap practice, because of the need to melt the oxide content of the pellet and to add lime to flux the gangue. The saving in energy consumption permitted by continuous charging of the pellets does not entirely compensate for this.

In view of these findings, the industry should be expected to treat the subject of direct reduction and the production of metallized iron units cautiously. It may be more realistic to expect that the U.S. industry within the next 15 years will import increasing quantities of metallized or partially reduced pellets. While a few plants may be built, the prospects for large-scale, direct-reduction processing in the United States within the next decade do not look optimistic.

E. RESEARCH AREAS

Five specific areas have been identified in this study where additional research is needed:

1. The possibility of cyanide formation under the following circumstances should be investigated:
    - injection of nitrogen during external desulfurization of hot metal, and
    - continuous recirculation of a $CO-N_2$ mixture over incandescent coke during dry quenching.
2. Quantitative measurements of fugitive and source emissions of carbon monoxide with non-combustion BOP gas collection systems should prove the acceptability of these hoods, including those taken during the transition periods at the beginning and the end of the blow, when the off-gases are not collected as a fuel.
3. A comparison of available equipment (lances, bells, etc.) for external desulfurization should be made to determine the economics and exact nature of the gaseous effluents as a function of the desulfurizing reagent used. The availability of desulfurizing agents (calcium carbide, magnesium, etc.) and the pollution/energy implications for industries supplying these products should not be neglected.
4. An increase in the quality of coke due to dry rather than wet quenching has been reported in the Russian literature. Should this be the case, a more efficient operation of the blast furnace would result and allow substantial savings, both in terms of coke rate and furnace productivity. A demonstration program is needed to substantiate this claim using U.S. coals.
5. The chemistry of the rotary kiln (e.g., SL/RN) is still not well-known. The pollution implications mentioned in this study are "best engineering judgment" and lack actual proof. The composition of the off-gases and the leaching properties of the coal, ash, and fine metallic discarded particles should receive the attention of research organizations.

III. INDUSTRY OVERVIEW

A. INDUSTRY OPERATIONS

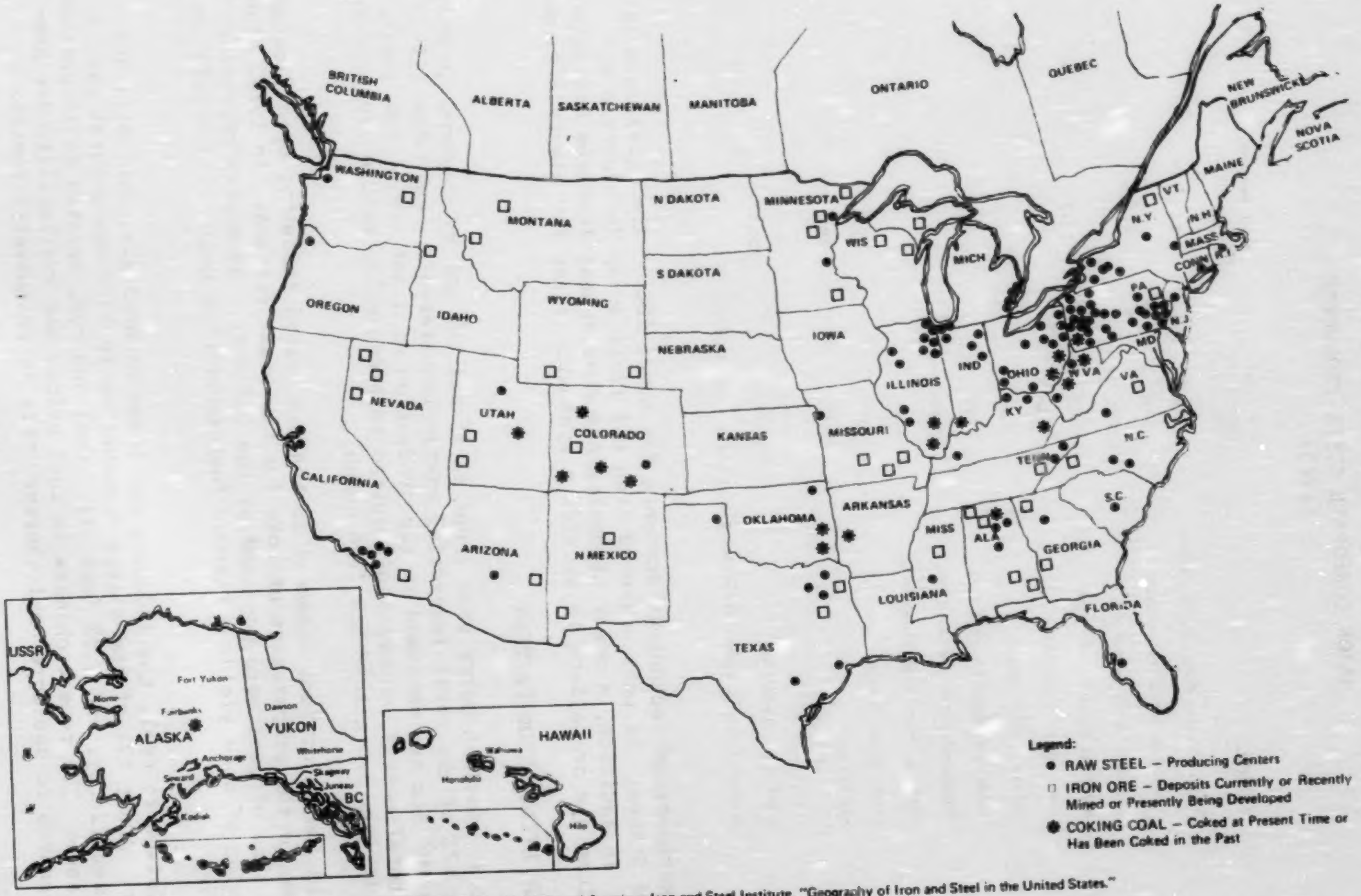
Although its share of world production has decreased, the United States has consistently ranked first or second among the world producers of steel. In 1950, the United States produced almost 50% of the world steel supply, but by 1973 its share had shrunk to barely 20%. During that same period, however, production increased from 90-100 million tons to about 150 million tons of raw steel.

The United States lost its self-sufficiency in iron ore production about the end of World War II, and imports have risen since to recent levels equivalent to almost 50% of domestic production, i.e., almost a third of domestic consumption of iron ore. The nation, however, is self-sufficient in the production of metallurgical coals needed for coke production and, in fact, is a major exporter of metallurgical coals to foreign steelmaking centers. The major fluxes for slagging the nonmetallic content, limestone, and dolomite are in adequate supply.

The industry comprises some 400 steel production and fabrication plants employing more than 500,000 people in 37 states. About 130 of these plants produced 146 million short tons of raw steel in 1974. The remainder are steel rerolling, finishing, fabrication plants. These figures exclude the mining operations for the raw materials and transportation and warehousing operations associated with the consumption of finished products. Figure III-1 shows the geographical distribution of the U.S. iron and steel industry. The major concentration of the industry operations occurs in the Ohio River Valley and states bordering the Great Lakes.

Ten major corporations accounted for about 80% of U.S. steel production in 1973. The largest of them, U.S. Steel Corporation, accounted for 23.2% of the national total, while the smallest in this group accounted for 2.1%. The details are shown in Table III-1. About half of the production in the "all others" category may be attributed to 19 smaller companies.

Two technological approaches are employed in the manufacture of raw steel, one using iron ore and one using scrap. In the iron ore-based technology, the blast furnace burns coke to produce iron in molten form as a high-carbon content hot metal which is further refined to steel by the selective oxidation of its impurities in a steelmaking furnace and by alloying additions. The molten steel is then cast as desired for rolling. Fluxes are added in the blast furnace to combine with the nonmetallic content of the iron ore to produce a molten slag. In 1974, about 80% of the raw steel was produced with this technology.


BRITISH COLUMBIA
ALBERTA
SASKATCHEWAN
MANITOBA
ONTARIO
QUEBEC
NEW BRUNSWICK
NOVA SCOTIA
WASHINGTON
MONTANA
N DAKOTA
MINNESOTA
OREGON
IDAHO
WYOMING
S DAKOTA
WIS
MICH
N.Y.
VT
N.H.
MAINE
MASS
CONN
R.I.
PA
N.J.
MD
IOWA
NEBRASKA
ILLINOIS
IND
OHIO
W VA
VA
KY
NEVADA
UTAH
COLORADO
KANSAS
MISSOURI
TENN
N.C.
CALIFORNIA
ARIZONA
N MEXICO
OKLAHOMA
ARKANSAS
MISS
ALA
GEORGIA
S.C.
LOUISIANA
TEXAS
FLORIDA
USSR
Fort Yukon
Nome
Fairbanks
ALASKA
Dawson
YUKON
Whitehorse
Anchorage
Seward
Skagway
Juneau
BC
Kodiak
HAWAII
Wahiawa
Honolulu
Hilo
Legend:
● RAW STEEL – Producing Centers
☐ IRON ORE – Deposits Currently or Recently Mined or Presently Being Developed
✱ COKING COAL – Coked at Present Time or Has Been Coked in the Past

SOURCE: Arthur D. Little and American Iron and Steel Institute, "Geography of Iron and Steel in the United States."

Figure III-1. Geographical Distribution of the U.S. Iron and Steel Industry

TABLE III-1

MAJOR CORPORATE STEEL PRODUCERS
(1973)

Company	Raw Steel Production (million tons)	Total National Production (%)
United States Steel Corporation	34.97	23.2
Bethlehem Steel Corporation	23.70	15.8
National Steel Corporation	11.32	7.5
Republic Steel Corporation	11.29	7.5
Armco Steel Corporation	9.46	6.3
Inland Steel Company	8.16	5.4
Jones and Laughlin Steel Corp.	7.99	5.3
Youngstown Sheet and Tube Co.	5.85	3.9
Wheeling Pittsburgh Steel Corp.	4.41	2.9
Kaiser Steel Corporation	3.17	2.1
All others	30.10	20.1
Total U.S. Production	150.42	100.0

Source: Steel Industry Financial Analysis for 1973, Iron Age

The scrap-based technology accounts for about 20% of the steel made in the United States. It uses selected iron and steel scrap in electric arc furnaces. In addition, a newer technological development involves directly reducing lump ore or pellets to provide a synthetic scrap for electric furnaces.

B. ENERGY UTILIZATION PATTERN

The U.S. steel industry uses about 6% of all the energy consumed in the nation, or 17% of the total industrial energy requirements (see Table III-2). About 24×10^6 Btu are consumed in the production of a net ton of raw steel. Thus, the total energy consumption required to produce 150 million tons of raw steel in 1973 was 3.6×10^{15} Btu (3.6 quads).

Coal is the major fuel consumed in the U.S. steel industry; specifically, coals suited to the preparation of coke for the blast furnace. In 1974, about 90 million tons of coal were consumed by the industry. As energy byproducts the production of coke yields a gaseous fuel (coke-oven gas), plus liquid tars and pitches.

In addition to coal, the industry purchases natural gas, fuel oil, and electricity. About 17% of the energy consumption in 1973 was natural gas, 5% purchased electricity, and 1.5% fuel oil. Coal and coal-derived fuels accounted for the balance. The recent changes in fuel prices and availability are generating pressures to use more coal wherever this is technically feasible.

TABLE III-2

RELATIVE CONSUMPTIONS OF ENERGY IN THE UNITED STATES (1973)

	10^{15} Btu (quads)	Percentage of Nation	Percentage of Industrial
Total Nation	75.560	100.0	-
Total Industrial	21.357	28.2	100.0
Steel Slabs from Ore	3.072*	4.1	14.4
Aluminum Ingots	1.120	1.5	5.3
Portland Cement	0.646	0.9	3.0
Gray Iron Castings	0.365	0.5	1.7
Copper Cathodes and Shapes	0.271	0.4	1.3
Glass Containers	0.217	0.3	1.0
Magnesium Metal	0.042	0.1	0.2

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*The 3.072×10^{15} figure is based on an average energy consumption of 24×10^6 Btu and 1973 production of 128 million tons. The tonnage discrepancy may be accounted for in the definition of crude steel and slabs from ore.

Source: Arthur D. Little, Inc., estimates.

The major consumption of energy occurs in the reduction of the iron ore to remove its oxygen content. This process step in the blast furnace sequence accounts for about 75% of the energy consumption per ton of raw steel. If the iron ore is directly reduced rather than smelted in the blast furnace, and the product is then smelted in an electric furnace to produce crude steel, the energy consumption increases substantially as discussed in Chapter IV. On the other hand, selected lower valued steam coals may be the basis for direct-reduction/electric-furnace steelmaking, whereas high valued metallurgical coals are a prerequisite for the blast-furnace method. Thus, fuel form, price, and availability may characterize energy conservation rather than actual consumption as energy units.

The two major sources of recycled fuel gas within the steel manufacturing complex are: coke-oven gas, a sulfur-containing, medium-Btu fuel gas produced in the manufacture of coke; and blast-furnace gas, a low-sulfur, low-Btu value fuel. A portion of the coke-oven gas is often utilized to provide the heat input to the ovens in which the coking reactions occur. A large portion of the blast furnace off-gas is employed to preheat the blast air in the regenerative stoves and fire the coke ovens. Gas streams not used in these processes may provide fuel for reheating and soaking furnaces or for the boiler house. Tar and pitch produced as byproducts from coke-making operations can be either sold or used as a fuel (e.g., by injection in the blast furnace).

IV. EVALUATION OF PROCESS OPTIONS

A. BACKGROUND

The major process steps in iron and steelmaking are: agglomeration of iron ore, cokemaking, blast furnace production of hot metal (molten pig iron), refining of the hot metal in a steelmaking furnace, and casting. The solidified product is then heated, rolled, heat-treated and, at times, coated to form a wide variety of end-products, such as steel plate, heavy structurals, rails, wire and wire products, cold finished bars, seamless pipe and tube, welded pipe, hot rolled sheet and strip, galvanized products, tin plate, and other plated products.

Although energy-conservation measures will prompt process changes in the steel-forming step, the major pollution consequences arising from process changes will be felt in the raw steelmaking sequence.

In addition to the integrated steel industry, which manufactures semi-finished and finished products from virgin raw materials supplemented by scrap, there is a semi-integrated industry based upon the electric furnace, which uses scrap as a raw material and manufactures the same type of products. The major pollution problems of this industry are associated with the electric furnace. These problems are discussed in connection with the melting of synthetic scrap made by the direct reduction process.

Of the many processes considered in the iron and steelmaking industry, the following four were chosen for analysis:

- Recovery of carbon monoxide from the basic oxygen process (BOP) vessel for its fuel value,
- Dry quenching of coke,
- Direct reduction of iron ore, and
- External desulfurization of blast furnace hot metal.

To compare the pollution characteristics, energy consumption, and economic attractiveness of these newer technological options, we developed a base line technology for each process option. Recognizing that there may be differences of opinion about the proper selection of a base line technology, we chose to define the smallest process sequence that would be a clear-cut design alternative, starting with similar raw materials and finishing with similar products. Thus, for the four process options selected, the base line technologies were defined as follows:

Recovery of Carbon Monoxide from BOP Vessels. We chose the conventional practice of burning the gas issuing from the BOP vessels in the collecting hood and then scrubbing the burned gases to remove particulates. The fuel value of the BOP off-gas is, therefore, lost in the base line. In the alternative process investigated, the CO-containing gases are prevented from burning, cleaned, and collected for their fuel value.

Dry Quenching of Coke (starting with hot coke as it is pushed from the coke oven). The base line technology chosen was the conventional wet quenching of coke. In both cases the coke is cooled to close to ambient temperature.

Direct Reduction. We chose the conventional coke oven-blast furnace-BOP vessel route for the base line. The direct reduction route includes the direct reduction units and electric furnaces. We started with iron ore pellets and finished with molten steel in both cases, with the same amount of scrap being recirculated to the steelmaking furnaces. We might have considered a direct reduction-blast furnace-BOP route.

External Desulfurization of Blast Furnace Hot Metal. Because of a growing demand for low-sulfur metallurgical coal, there has been considerable pressure to use higher-sulfur metallurgical coals for making coke. The most meaningful way of evaluating the desulfurization process would include:

- Establishing a base line technology whereby the blast furnace uses low sulfur coke (say, 0.8% S) and produces 2.6 million tons of hot metal annually, while meeting sulfur specifications (0.025% S in hot metal).
- Considering as an alternative technology the same blast furnace using a higher sulfur coke (say, 1.2% S) and producing also 2.6 million tons of hot metal per year. All other things being equal, the sulfur content of the hot metal would be higher (0.050%). To reduce this sulfur content, an external desulfurization station would be considered.

Because of the unprecedented recent demand for low-sulfur coal, it has become a premium-priced commodity compared to other coals being sold on the market. Premiums that are being paid for such low-sulfur coal depend upon the geographical considerations within the United States, demand for such low-sulfur coal in the industrial and utility sectors, the need of a steel company to get maximum productivity out of existing blast furnaces which, in turn, depends upon the demand for steel in a given year, and the like. Thus, setting a long-term value on coal depending upon sulfur content is a rather difficult exercise. Prices and price differences existing today would have probably little significance in the long term. Thus, to demonstrate that external desulfurization is an economically viable process to be considered when sulfur levels in the coke rise to 1.2% or higher, we chose an alternative way to indicate the competitive nature and economics of external desulfurization.

For purposes of this study, we assumed that a blast furnace designer would have two methods of coping with the higher-sulfur coals: (a) design a blast furnace for a given production of hot metal to accommodate a sufficient limestone fraction in the burden so the sulfur specifications would be met in the blast-furnace hot metal as tapped (0.025% sulfur), or (b) design a slightly smaller furnace with smaller limestone and coke rates and desulfurize the hot metal partially in the blast furnace (0.050% sulfur as tapped) and partially outside of the blast furnace, bringing the sulfur content to the 0.025% specification. Such a process is known as external desulfurization. While such an approach has its deficiencies, it provides a clear and consistent basis for comparing the economics of both options while using the same type coal for both base line and alternative process.

Each of these four process options was then evaluated on the basis of its energy conservation potential and the impact on pollution control that its implementation would generate. Capital and operating costs were developed and compared with the base line for both production and pollution equipment.

In each of the above comparisons, the focus was on new installations, even though many of the applications might be in old facilities (retrofitting). In older facilities the economic attractiveness depends upon the specific plant situation, location of the facilities within the plant, the amount of available land, logistical problems, and the like. Hence, it is difficult to generalize about the applicability of such processes to older facilities without doing a plant-by-plant analysis for each steel mill in the United States.

B. RECOVERY OF CARBON MONOXIDE FROM BOP VESSELS

1. Base Line Description

Our base line is a complete combustion system. The gases issuing from the mouth of the furnace are collected in a hood with a considerable infiltration of air, burned in the hood, and cooled and cleaned of particulates before being released to the atmosphere. The hood is steam- or water-cooled.

The hot gases leaving the basic oxygen furnace have a calorific value of approximately 350 Btu/scf and after collection and cooling will have a value of about 200-250 Btu/scf. In the United States, however, steelmakers have had little incentive to recover this heat, because they have had an adequate supply of inexpensive fuel. Thus, until 1961, most BOP installations used panel-type hoods that cool hot gases, but have no provision to recover the waste heat for reuse. More recently, a significant proportion of newer installations have utilized pressurized hood systems with membrane tube construction. These lend themselves to increased cooling water temperatures, or the generation of steam. However, waste heat recovery in the form of steam from these gases is difficult because the gas flow from the basic oxygen process is intermittent.

Although either electrostatic precipitators or wet scrubbers can be used for cleaning combustion products, fire and explosion hazards make the electrostatic precipitator system unsuitable for the collection of the carbon monoxide off-gas. Therefore, to ensure consistency in analysis, both base line and alternative technology include a wet scrubber system.

With conventional membrane hoods, the gases from the basic oxygen furnace are cooled to 1850°F and quenched in a venturi scrubber where they are further cooled to approximately 170°F. The quenched gases immediately enter a separating elbow where most of the liquid is separated from the gas stream. They are then led through a refractory-lined duct to the venturi scrubber. The scrubber is equipped with restricted throats which maintain a pressure drop in the range of 40 to 65 inches of water. The cleaned gas contains less than 0.05 grain of dust per cubic foot (0.11 gm/m^3). The cleaned gases leaving the scrubbers pass through an extraction fan and stack to the atmosphere.

The water treatment circuit consists of a thickener, a cooling tower, and a filter. The dust entrained in the water settles out as a sludge. Normally the cleaned water will contain less than 5 grains per gallon (100 mg/liter) of suspended solids. (Some steel companies claim less than 1 grain/gallon in the cleaned water.)

The schematic layout of such a plant is shown in Figure IV-1.

2. BOP Off-Gas Recovery

The BOP off-gas recovery systems collect and recover CO gas without combustion. The two prominent systems are the OG process and the IRSID-CAFL process.

a. The OG System

Figure IV-2 presents a schematic layout of an OG system. The gap between the vessel mouth and the collecting hood is minimized by a movable skirt. In the initial OG design, any space remaining between the skirt and the mouth of the furnace was closed off by a nitrogen seal. In recent installations, no nitrogen curtain seal is used. The space between the skirt and the vessel's mouth is closed as much as possible by lowering the skirt into the furnace nose section. During the oxygen blow, a slight negative pressure is maintained inside the hood.

In the process described by Rowe (1970), the skirt is attached to the lower section of the hood which subsequently leads the gases into the cooler. The upper section, which is equipped with the flux chute hole and the oxygen lance entry hole, is mounted on a carriage and may be moved away from its operating position to facilitate entry of the brick relining elevator. The necessary process fluxes are added to the BOP during the oxygen-blowing period through a system of gas seals.

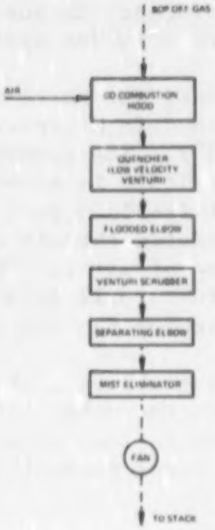
BOP OFF GAS
AIR
OD COMBUSTION HOOD
QUENCHER (LOW VELOCITY VENTURI)
FLOODED ELBOW
VENTURI SCRUBBER
SEPARATING ELBOW
MIST ELIMINATOR
FAN
TO STACK

Figure IV-1. Schematic Layout of Complete Combustion BOP Gas-Cleaning System

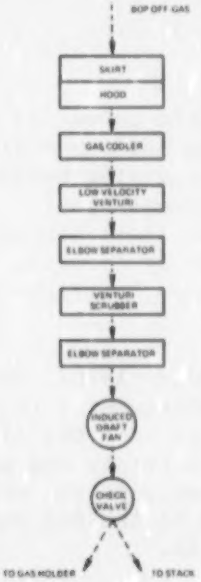
BOP OFF GAS
SKIRT
HOOD
GAS COOLER
LOW VELOCITY VENTURI
ELBOW SEPARATOR
VENTURI SCRUBBER
ELBOW SEPARATOR
INDUCED DRAFT FAN
CHECK VALVE
TO GAS HOLDER
TO STACK

Figure IV-2. Schematic Layout of the Non-Combustion BOP Off-Gas Recovery System (OG Process)

The gases pass through the upper section of the hood at a temperature of 2300°F and are cooled to approximately 1850°F in the hot gas cooler before entering the gas cooling plant. The gas-cooling section consists of a series of nested tubes supported in a mild steel, circular outer jacket. The wet scrubber used to clean the gas from the OG system is similar to that used in a plant with complete combustion.

The gases leaving the radiant section of the hood pass into a venturi quencher where they are cooled to an outlet temperature of about 170°F. At the same time, some 85% of the dust entrained in the gases is removed. The cooled gases leaving the venturi quencher pass through an elbow separator into a variable-throat venturi scrubber.

The adjustable throat acts both as a highly efficient dust-collecting unit and as a means of controlling the pressure in the waste gas hood. This system maintains a constant hood pressure during the oxygen blow by opening and closing the movable throat inside the venturi. The dust particles remaining in the waste gases after leaving the quencher are removed in the venturi scrubber. Finally, the cleaned gases pass through a second elbow separator and through a mist eliminator before being piped away as a clean fuel.

b. The IRSID-CAFL Process

The IRSID-CAFL process, described by Manbon (1973), is quite similar in concept to the OG process in that gas combustion is prevented by regulating the draft precisely. The gas collection equipment is comprised of a hood with a movable skirt. The pressure inside the hood is regulated so that the pressure differential between the flowing gases and the atmosphere is about 0.04-0.08 inch of water. The pressure in the system is regulated by a butterfly valve located upstream of the fan or by an adjustable venturi. The gases leave the hood and enter a spark box where entrained pieces of slag, refractory, ore, and such, drop out by gravity. The hoods and solids traps are water-jacketed, the heat being removed as low-pressure steam. The gas is then sprayed with water in a horizontal duct and vertical risers. Dust is removed in a venturi scrubber. The water treatment circuit consists of a thickener and cooling towers. The thickened material is dewatered in centrifuges or filters.

If the gas is collected in a gas holder, the system is purged at the beginning and end of each blow by controlling the position of the movable skirt. The skirt is in its raised position during charging and during the first two or three minutes of the blow. The raised skirt permits enough air to enter to ensure the complete combustion of relatively small amounts of gas coming from the converter. The skirt is then lowered and gas collection proceeds without combustion. At the end of the gas blow, as the flow of gas begins to decline, the skirt is again raised and the blowing is finished with complete combustion. This method of purging ensures process safety by preventing the accumulation of explosive gas mixtures.

3. Pollutant Emissions and Necessary Abatement

A generalized flowsheet illustrating the potential for pollutant emissions is shown in Figure IV-3.

a. Air Pollution Control

The non-combustion system is an alternative method for air pollution control. In the conventional system, along with the BOP off-gas, there is a considerable amount of air infiltration that results in combustion in the hood. A major advantage of a non-combustion system is that the volume of gases to be treated is reduced as much as 80%, since air infiltration is reduced. Because both gas volume and thermal load to the gas cooling system are reduced as combustion is eliminated, the gas-handling equipment can be considerably smaller than that of the combustion systems. This is also true during the start-up and finishing phases: although the gases are burned during these phases, they are generated at a much smaller rate than during the recovery phase.

Basic oxygen furnace dust, as it issues from the vessel, is black and is composed primarily of iron in varying stages of oxidation. It also includes small amounts of tramp elements, such as zinc, that come from the scrap charged to the furnace.

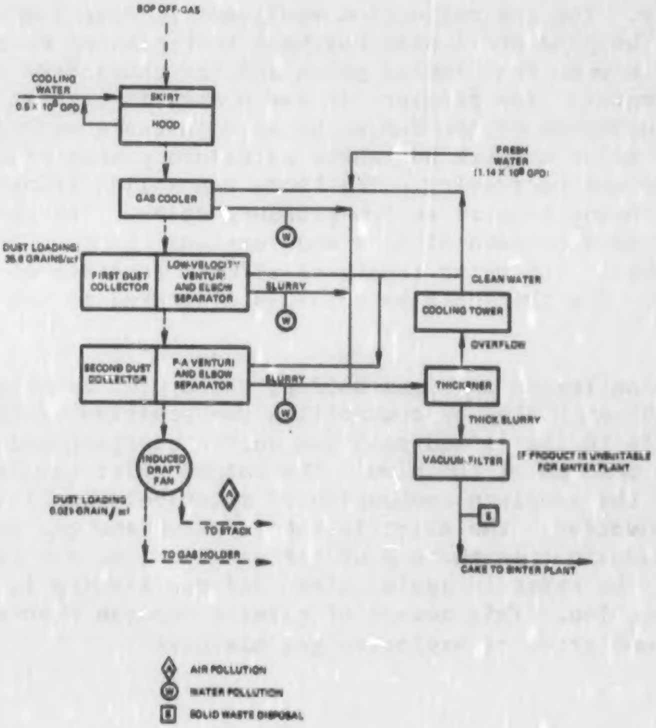
BOP OFF-GAS
COOLING WATER
0.5 × 10⁶ GPD
SKIRT
HOOD
FRESH WATER
(1.14 × 10⁶ GPD)
GAS COOLER
W
DUST LOADING: 35.6 GRAINS/scf
FIRST DUST COLLECTOR
LOW-VELOCITY VENTURI AND ELBOW SEPARATOR
SLURRY
CLEAN WATER
W
COOLING TOWER
OVERFLOW
SECOND DUST COLLECTOR
P-A VENTURI AND ELBOW SEPARATOR
SLURRY
THICKENER
W
THICK SLURRY
INDUCED DRAFT FAN
VACUUM FILTER
IF PRODUCT IS UNSUITABLE FOR SINTER PLANT
A
DUST LOADING 0.021 GRAIN/scf
TO STACK
S
TO GAS HOLDER
CAKE TO SINTER PLANT
A AIR POLLUTION
W WATER POLLUTION
S SOLID WASTE DISPOSAL

Figure IV-3. BOP Off-Gas Recovery without Combustion (IRSID-CAFL Process)

About 55 pounds of dust are produced per ton of steel in the BOP. When the carbon monoxide is burned with entrained air in the fume hood, the CO/CO_2 ratio becomes very low and the dust particle surfaces are subjected to high oxygen potentials causing oxidation and giving the dust a red color. Since the particles are swept and quenched before being oxidized completely, the dust has an outer surface of hematite surrounding a core of magnetite.

In the non-combustion processes the dust is composed mainly of FeO, magnetite, and small amounts of metallic iron. Because FeO and magnetite agglomerate more easily than hematite, the dust particles are larger than those obtained in conventional practice.

Tables IV-1 and IV-2 show the particle-size distribution for basic oxygen furnace dust with complete combustion and with non-combustion (OG) gas-cleaning systems. Although variations may be the result of operating practice, and analytical techniques, it is notable that OG dust contains only about 9% material below 5 microns compared with more than 25% below 1 micron in a combustion system.

Table IV-3 compares the dust composition in systems with and without combustion. Notable is the change in degree of oxidation represented by increased amounts of FeO and metallic iron in the OG dust. The metallic particulate material is cooled as it contacts the hood and stack walls and falls back into the converter. Yawata (1964) reports higher yields of metal for non-combustion systems in Japanese practice. One can speculate that this higher yield can be attributed to the lower gas volume in the non-combustion system, which results in more particles falling back into the converter. In the combustion systems, with their larger volumes of air infiltration, these particles would be carried away with the gases. However, some U.S. users of non-combustion systems state that these systems do not improve yields.

In both non-combustion and combustion systems, the dust collection equipment, consisting of high-energy scrubbers, gives a similar outlet concentration of dust. However, because the gas volumes are much reduced in the non-combustion case, the emission rate to the environment will be lower.

b. Water Pollution Control

Water pollution in BOP operations arises from the removal of air pollutants. The principal pollutant parameters are pH, suspended solids, and fluorides.

The water treatment circuits for both non-combustion and combustion gas treatment options are quite similar. Because of the lesser amount of fines in the non-combustion case - 9% material below 5 microns compared with more than 25% in a combustion system - settling characteristics are likely to be better. Furthermore, the water usage is lower in the non-combustion process. We have not seen any data that would indicate a substantial difference in the weight of dust generated in the combustion and non-combustion processes, so the size of solids/water separation equipment is not likely to change significantly.

TABLE IV-1

PARTICLE-SIZE DISTRIBUTION OF BASIC OXYGEN FURNACE DUST

Particle Diameter (microns)	Weight Percent
<1	25
1-65	15
65-90	20
90-110	15
>110	25

Source: Skelly (1966)

TABLE IV-2

PARTICLE-SIZE DISTRIBUTION OF OG PROCESS DUST

Particle Size (microns)	Weight Percent
<5	8.7
5-10	9.0
10-20	39.5
20-30	28.8
>30	14.0

Source: Yawata (1964)

TABLE IV-3

EFFECT OF OG PROCESS ON COMPOSITION OF BASIC OXYGEN FURNACE DUST
(weight percent)

Component	Normal Practice	OG Process
Fe total	59	75
Fe metal	--	10
Fe as FeO	1.6	62
Fe as Fe_3O_4, Fe_2O_3[a]	57.4	3
CaO	2	2
SiO_2	1	1

(a) Calculated by difference.

Source: Cavaghan (1970)

c. Solid Waste Disposal

Solid wastes from this air pollution control equipment consist of wet scrubber sludges. The composition of the dust is influenced by the nature of the scrap charged to the BOP. If clean uncoated home scrap is used, the dust consists primarily of iron oxides and can be recycled to the sinter strand. If purchased scrap is used, it may not be possible to control the composition closely; as a result, the dust and resultant sludge can contain Pb, Zn, Sn and so forth. Suitable care has to be taken in the disposal of this sludge to prevent leaching of hydroxide precipitates by groundwater. Despite the change in the oxidation state of non-combustion dust, there are no data to suggest significant changes in treatment and handling of the wastewaters and resultant sludges. The sludges are expected to be alkaline and should be amenable to disposal into appropriately designed and operated landfills.

Because of the high metal content, special attention should be given to preventing acidic leaching conditions from occurring, and appropriate efforts should be taken to mitigate percolation and run-off from the disposal site.

d. Energy Aspects

The non-combustion collection system, as a result of the lower gas volumes handled, generally consumes less electrical energy than the combustion system, as shown in Table IV-4.

TABLE IV-4

COMPARISON OF ENERGY USAGE IN NON-COMBUSTION AND TOTAL COMBUSTION SYSTEMS

	Non-Combustion	Total Combustion
Electricity, kWh/ton steel	8	14
Energy recoverable as gas, 10^6 Btu/ton steel	0.44	none

Source: Rowe (1970)

The main advantage of the non-combustion process is that it permits about half of the off-gases to be recovered. This represents 2000 cu ft/ton steel of a fuel gas with a calorific value of about 220 Btu/cu ft and a low-sulfur content. Such a gas, with proper burner design, may be used in a variety of steel mill applications - e.g., soaking pits and power generation.

4. Current Adoption Status

More than 100 units using non-combustion systems are either operating or being built in Japan, France, the United States, the United Kingdom, Belgium, and the U.S.S.R. At almost all of the U.S. installations the collected gas is presently flared but increasingly consideration is being given to collection, storage, and use of this low-Btu gas.

5. Economics of Non-Combustion and Combustion Systems

We have compared the capital and operating costs for the two systems for a three-vessel BOP shop with an annual raw steel capacity of 5.25 million tons. Both systems use high-energy wet scrubbers. Current designs call for a separate gas-cleaning facility for each converter for safety reasons. The total combustion system needs two gas-cleaning facilities for three converters.

The costs for the two systems are presented in Tables IV-5 and IV-6. Capital investment for the non-combustion system is high ($4.4 vs. $2.7/annual ton of capacity). With the recovered gas used as a fuel and priced at $2/million Btu, the total operating costs of the non-combustion system are lower than those of the combustion system ($0.66 vs. $1.12/ton of steel, respectively).

TABLE IV-5

COST STRUCTURE IN NEW NON-COMBUSTION SYSTEM

Annual Design Capacity: 5.25×10^6 tons

Capital Investment: \$$23 \times 10^6$ (\$4.4/annual ton)

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Energy [Details on Table IV-4]: Electric Power Purchased	kWh	0.016	8	0.128
Energy Credits: Gas	10^6 Btu	2.00	-0.44×10^6	-0.880
Direct Operating Labor (Wages)	Man-hr	7.00	0.005	0.035
Direct Supervisory Wages L	Man-hr	7.00	0.001	0.007
Maintenance Labor +	Man-hr	7.00	0.002	0.014
Maintenance Supervision S	Man-hr	7.00	--	--
Maintenance Materials and Supplies	(2% of Investment)			0.088
Labor Overhead	(35% L + S)			0.020
FIXED COSTS				
Plant Overhead	(65% L + S)			0.036
Local Taxes and Insurance	(2% Investment)			0.088
Depreciation 18 years				0.244
TOTAL PRODUCTION COSTS				-0.22
Return on Investment (pretax)	(20%)			0.88
TOTAL (Rounded)				0.66

TABLE IV-6

COST STRUCTURE IN NEW TOTAL COMBUSTION SYSTEM

Annual Design Capacity: 5.25 x 10^6 tons

Capital Investment: $14 x 10^6 ($2.7/annual ton)

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Energy [Details on Table IV-4]: Electric Power Purchased	kWh	0.016	14	0.224
Direct Operating Labor (Wages)	Man-hr	7.00	0.005	0.035
Direct Supervisory Wages L +	Man-hr	7.00	0.001	0.007
Maintenance Labor S	Man-hr	7.00	0.002	0.014
Maintenance Supervision	Man-hr	7.0	--	--
Maintenance Materials and Supplies	(2% Investment)			0.053
Labor Overhead	35% (L + S)			0.020
FIXED COSTS				
Plant Overhead	65% (L + S)			0.036
Local Taxes and Insurance	(2% Investment)			0.053
Depreciation	5.55% Investment			0.148
TOTAL PRODUCTION COSTS				0.59
Return on Investment (pretax)	(20%)			0.533
TOTAL (Rounded)				1.12

C. EXTERNAL DESULFURIZATION OF BLAST FURNACE HOT METAL

1. Sulfur Problem and Base Line Technology

Coke, containing some of the sulfur found in the coal used, is the major contributor to the total amount of sulfur entering the blast furnace. Other sources of sulfur in the blast furnace include fuel injections, the scrap mixed with the burden, and the minerals themselves (ore, limestone).

Only a negligible portion of the sulfur is found in the off-gases; most of the sulfur leaving the blast furnace appears in the liquid slag and hot metal. The capacity of the slag to retain sulfur is governed by its basicity. Detailed thermodynamic studies of this subject can be found in the literature (e.g., Ward, 1962); generally an increase in the basicity of the slag by adding more limestone increases the sulfur retaining capacity of the slag. The sulfur enters the slag as calcium sulfide. Since such limestone additions must be brought to temperature and calcined in the blast furnace, they increase the coke consumption, which in turn introduces more sulfur. Clearly, then, there is a limit to the amount to which this "internal" desulfurization process is viable. It may be advantageous to tap a hot metal containing more sulfur than specified, and to add to the process sequence a new step: the injection of desulfurization agents into the molten iron during its transfer from the blast furnace to the steelmaking furnace. These agents react with the dissolved sulfur and form a sulfide slag that can be disposed of. This new step is called external desulfurization.

There are other steps in the iron and steelmaking sequence where sulfur can be controlled to some extent. In the BOP or open-hearth shop, sophisticated slagging techniques can be used. However, they are expensive as they interfere with other chemistry adjustments and considerably decrease the productivity of the shop. Prior to casting, one may still make sulfur-controlling additions. However, such reagents are expensive, the yield decreases again, and the chemistry of the steel can easily be shifted beyond the final specifications.

Except for some special grades of free-machining steel in which a high sulfur content (0.1 - 0.33 wt%) is specified for ease of cutting, sulfur is largely a deleterious element that should be kept at a minimum. It causes (Ward, 1962) red shortness* and susceptibility to overheating in wrought steels and ingot cracking and low ductility in cast steels. It also tends to form solid inclusions with oxides and alloying elements. It has strong interaction coefficients with other alloying elements and, therefore, displaces the entire physical chemistry of the steel. Most steel specifications call for a sulfur content of 0.020 - 0.030 wt%, and there has been a tendency to reduce this range, as customers require better and better qualities of steel. Therefore, the most favorable condition occurs when the sulfur in the hot metal already is in the proper range (0.020-0.030 wt%).

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*The expression "red shortness" refers to poor formability at red temperature.

Unfortunately, some operators find it more and more difficult to obtain low-sulfur metallurgical coal. Unless they own mines of such coal, they find themselves many times using coal containing over 1.5% sulfur. The resulting coke typically contains 1.2% sulfur and the hot metal which they tap may contain 0.050 wt% sulfur and more. At this point, the cost of adding an external desulfurization step must be balanced against greater productivity of the blast furnace and savings in fuel and limestone.

Table IV-7 shows the basis for our comparison as explained at the beginning of this chapter: in both bases, we produce 2.6 million tons of hot metal per year, using coke containing 1.2% sulfur. In both bases, the hot metal brought to the BOP contains 0.025% dissolved sulfur. In the base case, this specification is achieved in the blast burnace. With external desulfurization, the hot metal contains 0.050% sulfur when it is tapped. It is further reduced to 0.025% sulfur on its way to the BOP at the desulfurization station.

Both blast furnaces call on exactly the same technology. As stated earlier, we considered new plants in both cases for purposes of consistency in our comparison. The greater productivity gained with external desulfurization implies an economy of scale in the design of a blast furnace of same capacity; coke and limestone costs are reduced, as well as BF gas credits.

Customarily, the gas-cleaning system of the blast furnace does not appear as a pollution-abatement device, as it is, in fact, a step in the production of a low-Btu fuel gas. The only air-cleaning technology of concern will therefore be associated with the external desulfurization station.

TABLE IV-7

DEFINITION OF THE BASE LINE AND OF THE EXTERNAL DESULFURIZATION OPTION

	Base Case	Option
Blast Furnace Capacity (million annual tons)	2.6	2.6
Coke Rate (lb/ton of hot metal)	1,060	1,030
Limestone Rate (lb/ton of hot metal)	665	450
Sulfur content of the coke (%)	1.2	1.2
Sulfur content of the hot metal, as tapped (%)	0.025	0.050
Desulfurizing agent per ton hot metal	-0-	1.4 lb of Mg
Sulfur content of the hot metal, delivered to BOP (%)	0.025	0.025

The scrubbing water of both the blast furnace and the external desulfurization station can be treated in the same plant.* Therefore, the wastewater treatment plant of the sequence blast furnace and external desulfurization station will be designed as one unit. The same base line technology is assumed as for the blast furnace described in this chapter under Section E (Direct Reduction).

2. Methods of External Desulfurization

a. Reagents

A number of solid reactants have been proposed and used, with calcium- and magnesium-based compounds being those most seriously considered.

Calcium has been used in various forms - in the metallic state (it boils at 2432°F), and as CaO, CaC_2 and $Ca(CN)_2$ - to desulfurize pig iron. Powdered lime reacts with sulfur in the presence of carbon and silicon to give CaS, CO and some form of lime-silica compound. Calcium carbide is the most effective. However, it has to be ground to less than 150 mesh, which is difficult and expensive. The powder must be kept dry, because it reacts readily when brought into contact with water. Finally, it generates considerable quantities of black fumes during this reaction.

Magnesium metal has been used in England in wire form with nitrogen as a carrier. This metal causes tremendous turbulence in the bath, essentially because it boils at quite a low temperature, 1157°F. However, the most common application of magnesium is through the Mag-Coke process. In the Mag-Coke process, the desulfurizer is prepared by preheating coke and immersing it in molten magnesium. Lumps weighing 2-5 lb and containing 45% Mg are produced, and these are stored in sealed drums to prevent hydration. The Mag-Coke is added under a graphite plunging bell to keep it at the bottom of the bath as long as possible. Magnesium sulfide floats to the surface and tends to thicken the slag.

Finally, magnesium aluminum alloys injected through nitrogen lances have proven to be effective desulfurizers, with considerably less fuming than carbon-bearing products.

b. Implementation and Technological Factors

Practical methods are continuously being sought by which this new operation can be integrated into the overall handling procedure of the hot metal between tapping and pouring into the BOP vessel. Agarwal (1971) proposed to combine hot metal mixing and external desulfurization in the arrangement shown in Figure IV-4. This idea certainly is interesting, but no current engineering

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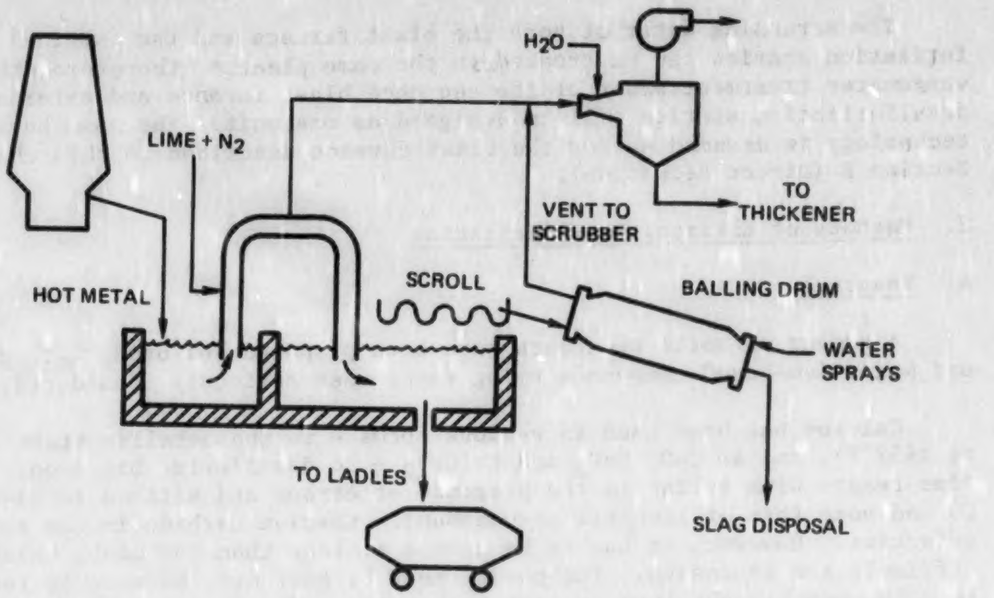
*This is our choice of a base line. Depending on the layout of the plant, the scrubbing water of the external desulfurization operation may actually be treated together with the BOP's scrubber water.


H2O
LIME + N2
TO THICKENER
VENT TO SCRUBBER
HOT METAL
SCROLL
BALLING DRUM
WATER SPRAYS
TO LADLES
SLAG DISPOSAL

SOURCE: Agarwal (1971).

Figure IV-4. Combination of Hot Metal Mixing and External Desulfurization

design of such arrangement exists. The reason probably is that simpler schemes are more appealing in an industry where productivity and reliability are key words. A few such schemes are discussed below:

Desulfurization in the ladle has the advantage of:

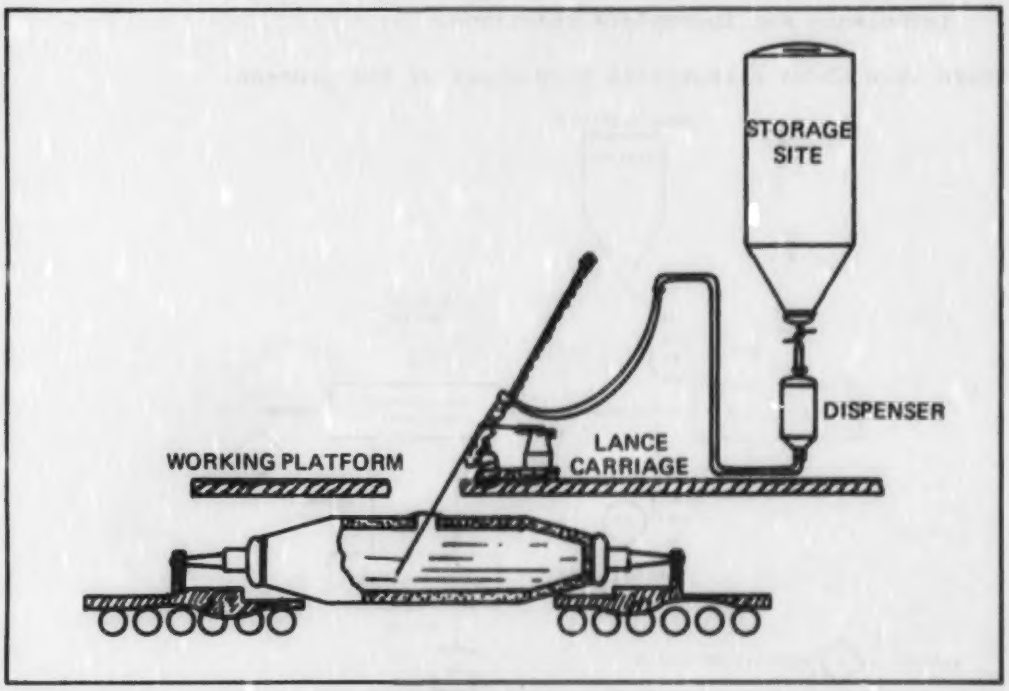
- A large contact area between the hot metal and the slag, which accelerates the rate of sulfur removal; and
- A favorable location for operation, the point where the torpedo car is poured into the ladle, because some air pollution control equipment is already likely to be in place there.

Some problems can arise for the following reasons:

- The ladles and cranes would be tied up longer, so larger capital expenditures for cranes and ladles would be necessary;
- It is more difficult to prevent the dilution of the gaseous effluents, so air pollution controls may have to be significantly larger, depending on the practice followed.

August Thyssen Hutte, among others, proposed to build a station over the railroad and to inject the desulfurizer through the narrow mouth of the torpedo car. Whenever practical, a lance is used to inject the reagent with nitrogen as a carrier. Such a design is shown in Figure IV-5. One major advantage is that a hood can be tightly fitted to the opening of the torpedo, so that gaseous emissions are easily collected. Drawbacks include the short life of the lances in the violently agitated metal bath, and the difficulty of using plunging graphite bells. Also, the slag formed may be difficult to remove as it tends to solidify or at least to be very viscous.

As graphite bells are not very convenient - they break and are difficult to operate through the opening of a torpedo car - the more likely injection system to be accepted is lancing with a nitrogen carrier a few feet from the bottom of the vessel. The nitrogen flow provides a beneficial stirring action. The lining of the vessel, however, has to be repaired more frequently because of the increased turbulence and larger exposure to hot metal. Nevertheless injection in the torpedo car seems to have gained a large audience, and we have used it as our external desulfurization option.



SOURCE: Meichsner (1974).

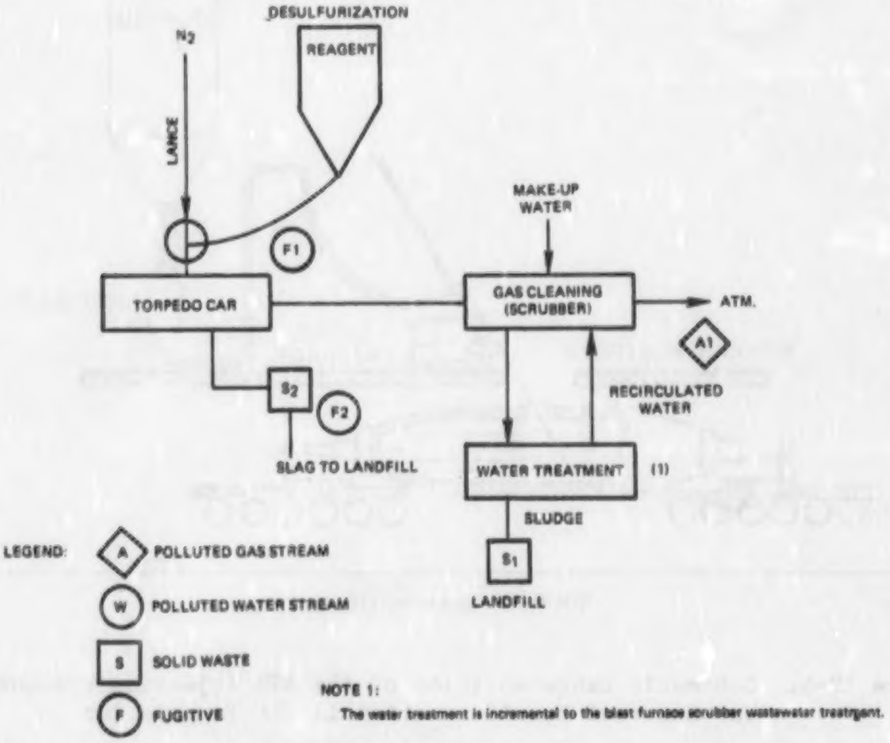
Figure IV-5. Schematic Representation of the ATH Injection Process for External Desulfurization in the Torpedo Car

c. Materials Balance

While variations can be expected, typically 2 to 5 lb of desulfurizer are required per ton of hot metal. The products and emissions include:

- The desulfurized steel, with a slightly lower silica content, on the order of 230 tons of hot metal for a torpedo car.
- A very viscous or solid slag. This slag amounts to 1 to 3% of the hot metal by volume. To reduce viscosity some thought has been given to additions of fluorspar, but it is not considered here as part of the process.
- Black smoke emissions and solid carbon in the slag when carbide is used.
- Possibly some cyanides when nitrogen is used as a carrier in the presence of carbon saturation. This is a potential area open to research, as no data has been brought to our attention on this subject.
- Various amounts of particulate emissions to the air because of turbulence and incomplete reactions.

Figure IV-6 shows a tentative flow chart of the process.


DESULFURIZATION
REAGENT
N_2
LANCE
F1
TORPEDO CAR
S_2
F2
SLAG TO LANDFILL
MAKE-UP WATER
GAS CLEANING (SCRUBBER)
ATM.
A1
RECIRCULATED WATER
WATER TREATMENT
(1)
SLUDGE
S_1
LANDFILL
LEGEND:
A POLLUTED GAS STREAM
W POLLUTED WATER STREAM
S SOLID WASTE
F FUGITIVE

NOTE 1:
The water treatment is incremental to the blast furnace scrubber wastewater treatment.

Figure IV-6. Flow Diagram for External Desulfurization in the Torpedo Car

d. Pollution Control

(1) Air Pollution Control

The gaseous emissions from desulfurization are essentially a nitrogen exhaust that contains particulates such as iron oxides, unreacted desulfurizer, and product slag. Since lancing with nitrogen is not a combustion process, the particulates which are produced should be more the result of entrainment than of metal condensations. Hence, the mean median diameter of the particulates is expected to be larger than that of BOP or blast furnace particulates, for example. This larger size should make the particulates easier to remove from the gas stream. Since nitrogen lancing generates an inert gas rather than a combustible gas, as found in blast furnace or BOP exhausts, problems of designing and maintaining a collection hood for the system should be greatly reduced and should result in a high degree of collection before the air pollution control equipment.

Finally, cyanide or traces of other nitrogen compounds might be present in the exhaust gas as they are in blast furnace gases. However, since nitrogen is relatively inert at the desulfurizing temperatures, we believe these compounds are not likely to be present in the exhaust of external desulfurization processes.* Therefore, an adequate control system should consist of a refractory-lined hood over the torpedo car opening, connected with a high-energy venturi scrubber to remove the particulates.

The design bases for such a system are taken as 26,500 actual cu ft/min (ACFM) for 50% of the total operating time and no flow the remaining time. With an estimated dust loading of 0.0025 lb/scf, this system should be capable of meeting present process weight-based emissions limitations. The capital and operating costs of such a system are shown in Table IV-8.

(2) Water Pollution Control

The wet scrubber chosen to control exhaust gas emissions from the desulfurization step will generate a wastewater stream. Based on the previous estimates (0.0025 lb of dust per cubic foot of gas, and an actual gas flow rate through the scrubber of approximately 26,500 cu ft/min for 50% of total operating time), the untreated scrubber water will be as follows:

flow rate - 381,600 gpd (instantaneous)
- 190,800 gpd (actual 24-hour flow)

suspended solids - 29,900 mg/liter (47,700 lb/day).

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*In the absence of specific data, we are unable to confirm this hypothesis, and this may well be an open area for research.

TABLE IV-8

AIR POLLUTION CONTROL COSTS FOR THE EXTERNAL DESULFURIZATION STATION
(Basis: 2.6 million tons of hot metal/yr)

CAPITAL INVESTMENT (CI)	$1,241,000
ANNUAL OPERATING COST	
Variable Costs	
Labor, (incld Supr + Overhead) (Total)	3,400
Maintenance @ 5% of CI	62,100
Utilities	
- Electric Power 220 kWh/10^6 scf @ $0.016/kWh	18,500
- Water, 100 gal/min @ $0.20/$10^3$ gal	5,300
TOTAL	$ 89,300
FIXED COSTS	
Depreciation 18 years	68,900
Taxes and Insurance @ 2% of CI	24,800
Total Fixed Costs	93,700
Total Production Cost	183,000
Pretax Return @ 20% of CI	248,200
TOTAL	$ 431,200
$/Ton of Steel	0.17

For purposes of this study it has been assumed that gravity settling for removal of suspended solids in a mechanical clarifier will be adequate to meet effluent limitations. (Furthermore, it is assumed that water from the clarifier will be recycled to the scrubber.) Although there might be some sulfides in the scrubber water (expected to be in the form of relatively insoluble compounds rather than free ions) and it is uncertain if cyanides would be present, the estimated capital and operating costs for wastewater treatment do not include processes for filtration or cyanide or sulfide removal.

Because virtually no hydrogen is present in the desulfurization process, phenol and ammonia will not be present in the scrubber water and no fluorides are expected. The expected condition of the treated desulfurization scrubber water is shown on Table IV-9.

To properly assess the water pollution control implications of an external desulfurization operation, it is necessary to compare the treated wastewater effluent from the base line blast furnace with the treated effluent from a blast furnace, plus an external desulfurization unit. A comparison of treated effluents is shown in Table IV-10. In this comparison the blast furnace scrubber water is subjected to the "Best Available Technology Economically Achievable (BATEA)," the 1983 treatment level recommended in the EPA Development Document. This basis was chosen because it is anticipated that any installations would not be completed before either the effective date of the 1983 standards, or that new source performance standards would be equally as stringent. This treatment level consists of clarification with a high degree

TABLE IV-9

EXPECTED COMPOSITION OF TREATED SCRUBBER WATER FROM DESULFURIZATION

Flow Rate (20% blowdown from recycled scrubber water)	- 76,300 gpd (instantaneous) - 38,150 gpd (actual 24-hr flow)

Parameter	Waste Load (lb/day)
Suspended Solids	16
Cyanide	Small amounts may be present
Phenol	Not present
Ammonia	Not present
Fluoride	Not present
Sulfides	May be present as insoluble compounds

An estimation of the incremental costs of treating the desulfurization scrubber water is shown in Table IV-12. The wastewater treatment system consists of clarification plus sludge dewatering via vacuum filtration. Eighty percent of the treated water is recycled to the scrubber.

TABLE IV-10

COMPARISON OF TREATED EFFLUENT WASTEWATER LOAD

Parameter	Blast Furnace (1) (Base Case)		Blast Furnace (1) plus External Desulfurization (2)	
	(lb/day)	(mg/l)	(lb/day)	(mg/l)
Suspended Solids	74	10	90	11.6
Cyanide (5)	1.9	0.25	≥1.9 (3)	≥0.24
Phenol	3.7	0.5	3.7	0.48
Ammonia (as NH_3)	74	10	74	9.6
Sulfide	2.2	0.3	≥2.2 (4)	≥0.29
Fluoride	148	20	148	19.2
Flow Rate	890,000 gpd		920,000 gpd	

Notes:
1. Blast furnace scrubber water in both cases is subjected to "Best Available Technology Economically Achievable" (1983).
2. External desulfurization scrubber water is subjected only to clarification for suspended solids removal.
3. Cyanide may be present in external desulfurization scrubber water, but has been assumed absent or inconsequential.
4. Low-solubility sulfide compounds may be present in external desulfurization water.
5. Cyanide amenable to alkaline chlorination.

of treated effluent recycle (97%). The blowdown stream from the scrubber water recycle loop is then subjected to alkaline chlorination for the removal of cyanide followed by neutralization, filtration, and carbon adsorption. The overall purpose of the treatment is to remove cyanide, phenol, ammonia, fluorides, and sulfides. As can be seen from Table IV-10, the additional waste load imposed by the incorporation of external desulfurization is a very small increment of the base line blast furnace.

An estimation of the wastewater treatment costs of the base line furnace is shown in Table IV-11, and the external desulfurization incremental waste water treatment costs are presented in Table IV-12. The wastewater treatment system for external desulfurization consists of clarification plus sludge dewatering via vacuum filtration with eight percent of the treated water recycled to the scrubber.

(3) Solid Waste

There are two sources of solid waste from the external desulfurization process: slag and sludge from the wastewater treatment. With the same sulfur content in the coke, incorporation of external desulfurization in the steelmaking sequence permits a lower limestone usage rate in the blast furnace. Lower limestone usage results in less slag generation. It is estimated that a blast furnace, coupled with external desulfurization, will produce 120 lb less slag/ton than a blast furnace without external desulfurization. Since the external desulfurization process itself produces an estimated 9 lb/ton of slag, net reduction in slag generation is about 111 lb/ton. Thus, an operation of 2.6 million ton/yr capacity employing external desulfurization will reduce overall slag generation by approximately 144,300 ton/yr.

The wastewater treatment system will produce a dewatered sludge estimated to contain 35% solids. It is estimated that 24,000 tons of sludge will be generated annually. If cyanide is present in the scrubber water, it will also be present in the liquid fraction of the sludge, because the common practice is to effect solids removal prior to cyanide destruction. Although the chemical form of the cyanides is not known, care should be taken to dispose of the sludge in a manner that will avoid groundwater contamination.

Solid waste disposal costs for the external desulfurization are given in Table IV-13. Use of the external desulfurization process will reduce overall solid waste generation by 120,300 ton/yr, which in turn will reduce solid waste disposal cost by $0.23/ton of steel, based on an estimated cost/ton of sludge and slag disposal of $5.

Total pollution control costs at the external desulfurizing station are $0.36/ton of hot metal. About half of these costs are attributable to air pollution control costs. Table IV-14 compares the total pollution control costs of both alternatives.

TABLE IV-11

BLAST FURNACE WASTEWATER TREATMENT COSTS
(Basis: 2.6 million tons of hot metal/yr)

Capital Investment: (CI)	$ 14.7 million dollars
Annual Operating Costs:	
Direct Operating & Maintenance Labor (L) @ $7 man-hr.	$ 320,000
Supervision (S) @ 15% (L)	48,000
Labor Overhead @ 35% (L+S)	129,000
Chemicals:	731,000
Power: 17.8×10^6 kWh @ $0.016	283,000
Fuel: 58.6×10^{10} Btu @ $\$2/10^6$ Btu	1,172,000
Maintenance & Materials: @ 4% CI	588,000
Total Operating Costs:	$3,272,000
Plant Overhead @ 65% (L+S)	$ 239,000
Local Taxes & Insurance @ 2% of CI	294,000
Depreciation (18 years)	817,000
ROI @ 20% CI (pre-tax)	2,940,000
Total	$7,562,000

Cost/ton of hot metal: $2.91

TABLE IV-12

EXTERNAL DESULFURIZATION INCREMENTAL WASTEWATER TREATMENT COSTS
(Basis: 2.6 million tons of hot metal/yr)

Capital Investment: $510,000

	Cost/Unit Quantity	Quantity/Ton of Product	$/Ton of hot metal
VARIABLE COSTS			
Operating & Maintenance Labor (L)	$ 7.00/ man-hr	0.00292/ man-hr	0.0205
Supervision (S) 15%(L)	—	—	0.0030
Maintenance @ 4% of CI	—	—	0.0099
Chemicals include:			
• Sulfuric Acid	$51.30/ton	0.11 lb	0.0028
Electric Power	$0.016/kWh	0.138 kWh	0.0022
Labor Overhead (L+S) 35%	—	—	0.0082
TOTAL VARIABLE COSTS	—	—	0.0466
FIXED COSTS			
Plant Overhead (L+S) 65%	—	—	0.0133
Taxes & Insurance (@ 2% of CI)	—	—	0.0039
Depreciation (18 years)	—	—	0.0109
TOTAL FIXED COST	—	—	0.0301
TOTAL ANNUAL COST	—	—	0.0767
RETURN ON INVESTMENT (Pretax) (@ 20% of CI)	—	—	0.0392
TOTAL	—	—	0.1159

TABLE IV-13

EXTERNAL DESULFURIZATION SOLID WASTE DISPOSAL COSTS
(Basis: 2.6 million tons of hot metal/yr)

Material	Annual Quantity (ton)	Disposal Cost ($/ton)	Quantity/ Ton of Product	$/Ton of Product
Wastewater Treatment Sludge (35% Solids)	24,900	5.00	0.0096	0.048
External Desulfurization Slag	11,700	5.00	0.0045	0.022
TOTAL SOLID WASTE	36,600	5.00	0.0141	0.070

TABLE IV-14

SUMMARY OF THE POLLUTION COSTS WITH AND WITHOUT EXTERNAL DESULFURIZATION
(Basis: 2.6 million tons of hot metal/yr)

	BASE CASE		OPTION	
	Capital Cost ($)	Operating Cost $/ton	Capital Cost ($)	Operating Cost $/ton
Air Pollution Control				
Blast Furnace *	-0-	-0-	-0-	-0-
Desulfurizing Station	-0-	-0-	1,241,000	0.17
Wastewater Treatment				
Blast Furnace	14,700,000	2.91	14,700,000	2.91
Desulfurizing Station	-0-	-0-	510,000	0.12
Solid Waste Disposal				
Blast Furnace	-0-	1.66	-0-	1.15
Desulfurizing Station	-0-	-0-	-0-	0.07
TOTAL	14,700,000	4.57	16,451,000	4.42

---

*No air production control cost is shown here for the blast furnace because the gas cleaning devices are considered productive equipment in the generation of a low-Btu fuel gas. (See text.)

e. Energy Considerations

The hot metal that has been externally desulfurized is only slightly cooler (15-30°F) than when it was tapped, because the heat of desulfurization partly compensates for the heat losses from the time delay. Its silicon and possibly its manganese content are lower, but the extent of this depletion does not significantly affect the ability of the BOP to melt scrap. Thus, except for the energy going into the preparation of the desulfurizing agent and into the preparation of nitrogen, the desulfurization station cannot be considered an energy-consuming unit.

Consequently, the energy implications of the process lie entirely with the blast furnace operation. The amount of limestone charged to the blast furnace is basically a function of the gangue and sulfur coming with the iron oxides and coke as well as the desired sulfur and silica level required in the hot metal. Increasing the limestone flux to control increased amounts of sulfur requires additional coke to meet the corresponding heat requirement. Since calcium sulfide has a limited solubility in slag, it may even be necessary to add silica. The additional coke, in turn, brings more sulfur that must be controlled. This is quantified in an example shown in Table IV-15. If the coke contains 1.2% sulfur, then the hot metal can be produced with 0.050% sulfur and externally desulfurized to 0.025% sulfur. To obtain the same sulfur level in the blast furnace would require an estimated additional 30 pounds of coke. External desulfurization, therefore, allows high-sulfur metallurgical coal to be used without any penalty on a Btu basis.

TABLE IV-15

COMPARISON OF ENERGY CONSUMPTION WITH AND WITHOUT EXTERNAL DESULFURIZATION

	Base Case 10^6 Btu	Option 10^6 Btu	
Blast Furnace:			
Coke[1]	13.25	12.87	
Electricity[2]	0.26	0.25	
BF Gas Credit	(3.80)	(3.69)	
Total Production:	9.71	9.43	
Pollution Controls			
Wastewater Treatment:			
Fuel	0.07	0.07	(3)
Electricity[2]	0.22	0.22	(3)
Air Pollution Control:			
Electricity[2]	--	0.004	
Total Pollution	0.29	0.294	
Total:	10.00	9.724	

Notes:
1. 1 ton of coke = 25 x 10^6 Btu
2. 1 kWh = 10,500 Btu at the power source.
3. The energy required to treat scrubbing water from the desulfurizing station is negligible.

f. Cost Factors

As mentioned earlier, external desulfurization is linked to blast furnace practice. An economic evaluation of this option was made recently by Ward (1975) for a particular plant of the British Steel Corporation (Appleby-Frodingham). His results are summarized in Figure IV-7. They show that meeting common sulfur specifications (0.020-0.030) in the blast furnace is increasingly difficult and expensive when the sulfur content of the coke reaches 1-1.2 wt%. Similar conditions were chosen for this study, and indeed they appear to represent the point of indifference where either technology seems to be equally attractive. We expect that less favorable conditions regarding the price and quality of the blast furnace feedstock (coke and limestone) or more stringent hot metal specifications would favor external desulfurization, whereas more lenient conditions would favor the traditional practice.

(1) Capital Costs

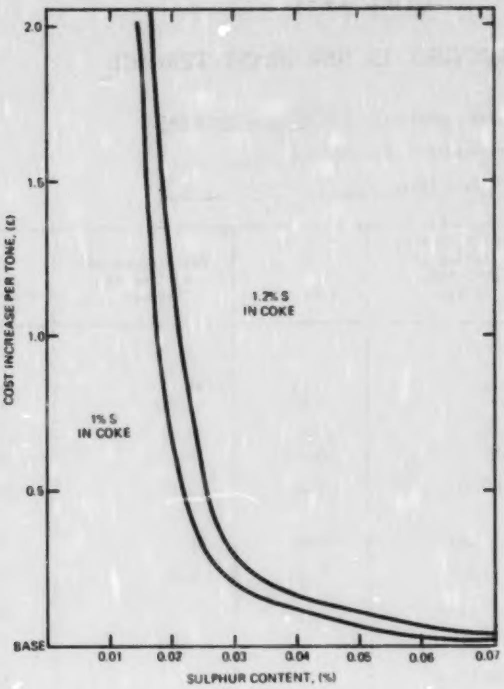
The blast furnace of the base line was estimated at $156 million. As the alternative practice increases the productivity of a blast furnace of this category by 3.6%, a slightly smaller blast furnace was associated with the external desulfurization station to produce the same quantity (2.6×10^6 ton/yr) of hot metal. Its investment cost is estimated to be about $152 million.

The capital cost estimates of the desulfurizing station include $900,000 for the station itself, and $1,240,000 for the air pollution abatement equipment (wet scrubber). These costs do not include investments for intrastructure such as additional railway track for a desulfurizing station. The wastewater treatment plant is common to the blast furnace and the desulfurizing station. The latter incurs an incremental capital investment of $510,000 to a base case of $14,700,000. The difference between the two routes is summarized in Table IV-16 and is not significant.

(2) Operating Costs

The operating costs of the base line blast furnace, the alternative operation with a smaller blast furnace and external desulfurizing station are detailed in Tables IV-17, IV-18 and IV-19, respectively.

The new option reduces the cost of hot metal as tapped from the blast furnace from $105.99 to $103.28 per ton. The cost of operating the desulfurizing station is $2.07 and the associated pollution control cost is $0.36/ton of hot metal, so that the cost of a ton of hot metal delivered to the BOP shop is $105.71 with the new route. The difference between the two routes is $0.28/ton of hot metal. This is well within the accuracy of these calculations, but does suggest that cost would not be an obstacle to implementation under the assumptions made in this analysis.



NOTE: *1£ × $2.03

SOURCE: Ward (1975)

Figure IV-7. Relationship between Cost of Ironmaking and Sulfur in Iron

TABLE IV-16

COST COMPARISON BETWEEN THE TWO ROUTES
(with and without external desulfurization)

	Base Line	Option
Capital Cost[1] ($)		
Blast Furnace	156,000,000	152,000,000
Desulfurization Station	---	900,000
Pollution Control	14,700,000	16,451,000
Total	170,700,000	169,351,000
Operating Costs[2] ($/ton of hot metal)	$105.99	$105.71

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(1) Basis: 2.6 x 10^6 ton/yr of hot metal
(2) Includes 20% ROI and pollution control costs

TABLE IV-17

COST STRUCTURE IN NEW BLAST FURNACE

Annual Design Capacity: 2.6 x 10^6 tons hot metal

Capital Investment (CI): $156 million

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials: Pellets	ltu[a]	0.45	84.7	38.11
Limestone	ton	5.00	0.332	1.66
Energy: Purchased Coke	ton	90.0	0.53	47.70
Electrical Power Purchased	kWh	0.016	25.	0.40
Energy Credits: Blast Furnace Gas	10^6 Btu	2.0	3.8	(7.60)
Water: Process (Consumption) Cooling (circulating Rate)	10^3 gal	0.05	11	0.55
Direct Operating Labor (Wages) L	Man-hr	7.00	0.10	0.70
Direct Supervisory Wages +	15% Labor			0.11
Maintenance Labor and Mat'l. S	5% Inv.			3.00
Labor Overhead	35% L + S			0.28
Misc. Variable Costs/Credits:				
slag sampling				0.25
scrap credit	ton	80.00	0.01	(0.80)
TOTAL VARIABLE COSTS				84.36
FIXED COSTS				
Plant Overhead	65% L + S			0.53
Local Taxes and Insurance	2% Inv.			1.20
Depreciation	5.55%			3.33
TOTAL PRODUCTION COSTS				89.42
Return on Investment (pretax)	20% CI			12.00
POLLUTION CONTROL				4.57
TOTAL				105.99

[a] long ton unit - 22.4 lb of coal contained Fe.

TABLE IV-18

COST STRUCTURE IN NEW BLAST FURNACE
(Reduced Coke Rate)

Annual Design Capacity: 2.6 x 10^6 tons hot metal

Capital Investment (CI): $152 million

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials: Pellets	ltu	0.45	84.7	38.11
Limestone	ton	5.00	0.225	1.12
Energy: Purchased Coke	ton	90.00	0.515	46.35
Electric Power Purchased	kWh	0.016	24	0.38
Energy Credits: Blast Furnace Gas	10^6 Btu	2.00	3.69	(7.38)
Water: Cooling (Circulating Rate)	10^3 gal	0.05	10.6	0.53
Direct Operating Labor (Wages) L	Man-hr	7.00	0.10	0.70
Direct Supervisory Wages +	15% Labor			0.11
Maintenance Labor S				
Maintenance Materials and Supplies	5% Inv.			2.92
Labor Overhead	35% L + S			0.28
Misc. Variable Costs/Credits[(a)]:				
Slag Sampling				0.25
Scrap Credit	ton	80.00	0.01	(0.80)
TOTAL VARIABLE COSTS				82.57
FIXED COSTS				
Plant Overhead	65% (L + S)			0.53
Local Taxes and Insturance	2% Inv.			1.17
Depreciation 18 years				3.25
TOTAL PRODUCTION COSTS				87.52
Return on Investment (pretax)	20% CI			11.70
POLLUTION CONTROL				4.06
TOTAL				103.28

(a) long ton unit = 22.4 lbs of contained Fe.

TABLE IV-19

COST STRUCTURE IN NEW EXTERNAL DESULFURIZATION

Annual Design Capacity: 2.6 x 10^6 tons hot metal

Capital Investment (CI): $900,000

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials: Desulfurizer	lb	0.67	2	1.71
Nitrogen	1,000 scf	0.16	0.870	0.14
Hot Metal (S=0.048%)	ton			103.28
Direct Operating Labor (Wages) L	Man-hr	7.00	0.0066	0.047
Direct Supervisory Wages (S)	L		15%L	0.007
Maintenance Materials and Supplies	CI		4% CI	0.014
Labor Overhead	L + S		35% (L + S)	0.02
TOTAL VARIABLE COSTS				105.22
FIXED COSTS				
Plant Overhead	L + S		65% (L + S)	0.035
Local Taxes and Insurance	CI		2% CI	0.007
Depreciation	CI		5.6% CI	0.02
TOTAL PRODUCTION COSTS				105.22
Return on Investment (pretax)				0.07
POLLUTION CONTROL				0.36
TOTAL				105.71

g. Current Adoption Status and Future Outlook

The average sulfur content of the hot metal has been continuously increasing and can be expected to reach 0.060 - 0.070 wt% in the next 15 years. External desulfurization is most likely to be used, therefore, to bring sulfur from 0.050% or more down to 0.020-0.030% for production of ordinary steels.

Various forms of external desulfurization have been practiced in Europe for many years. Soda ash was used at first; erratic results, pollution problems, wear of refractory lining and difficulty in deslagging prompted a switch to calcium-and magnesium-based processes. The process studied in some detail in this study might be the one with the widest conceptual acceptance: a reagent (magnesium alloy, calcium compound) is injected in the torpedo car through a nitrogen lance.

The concept of external desulfurization is not new to American steelmakers. However, they have started partial and temporary pilot tests and operations only recently. The general feeling is that the industry will adopt this practice more widely in the 15 years to come because:

- low-sulfur metallurgical coal may well be at a premium;
- it is not a very capital-intensive investment; and
- it has the potential to be retrofitted to existing facilities.

Where space is available and it is logistically feasible to set up a desulfurizing station, older blast furnaces can easily accommodate external desulfurization. This can be an interesting option for a steel company faced with the prospects of using higher-sulfur coal. In this way, productivity can be maintained at a relatively small capital investment. However, in order to assess more accurately how many steel mills will use higher-sulfur metallurgical coals and which of these mills can retrofit external desulfurizing stations into the present plant layout a detailed economic assessment on a plant-by-plant basis would be required.

D. DRY QUENCHING OF COKE

1. Description of the Base Line

Current technology involves wet quenching of coke and forms the base line for this analysis. In wet quenching, hot coke (at 1900-2000°F) is delivered in a coke car to a tower where the coke is quenched with water, thereby producing large quantities of steam that are vented to the atmosphere. The coke car is designed to allow the excess water to drain. This water is often recirculated. Wet quenching results in coke with an average moisture content of 2.5%.

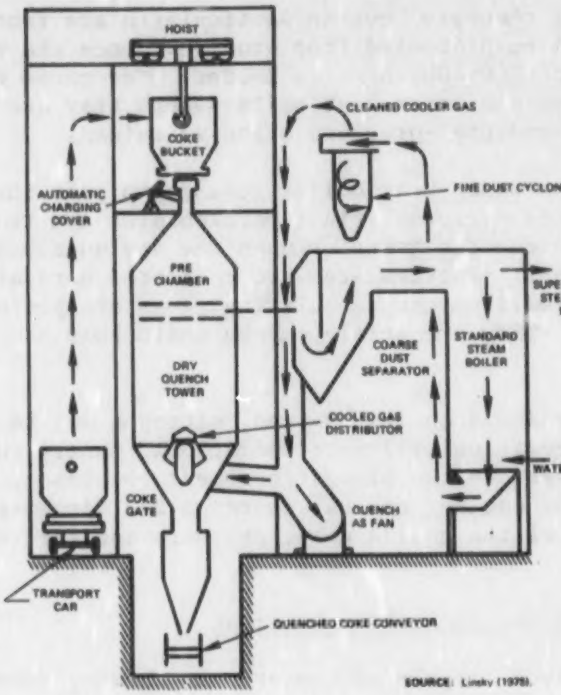
Wet quenching of coke creates air pollution if the quenching water contains contaminants, e.g., flushing liquor from the coke byproduct recovery plant. In such cases, pollutants are vaporized and carried off in the "cloud" or "plume." The use of clean water minimizes the emission of objectionable organic vapors, and the installation of baffles in the quench tower is claimed to remove solid particulates satisfactorily (A.D. Little, Inc., 1975)

2. Description of the Dry Quenching Process

In dry quenching of coke, the hot coke pushed from the ovens is cooled in a closed system. Dry quenching uses "inert" gases to extract heat from incandescent coke by direct contact. The heat is then recovered in waste heat boilers or by other techniques. The inert gases can be generated from an initial intake of air which reacts with the hot coke to form a quenching gas of the following composition: 14.5% CO_2, 0.4% O_2, 10.6% CO, 2% H_2 and 72.5% N_2 (Linsky, 1975).

Except for the periodic introduction of hot coke with entrained gases, dry quenching is a closed-cycle operation on the gas side. Because oxygen is largely absent, the danger of explosion is minimized. Nevertheless, explosion precautions must be taken and the composition of circulating gases must be monitored and controlled by the addition of nitrogen.

Quenching plants in the U.S.S.R. are comprised of independent "tower boiler" blocks. Each block includes a cooling tower, a waste-heat boiler, dust collectors, and a gas-blower. The following process description is based on an article by Linsky (1975) with the flow diagram shown in Figure IV-8. The incandescent coke, which is between 1900°F and 2000°F, is initially pushed from the coke oven into a special car bucket designed to receive coke from only one oven at a time. An electric locomotive transports the bucket to the cooling tower, and a vertical hoist lifts the bucket from the locomotive to the tower's cl rging hole (near the top of the tower). As the hoist approaches the charg- i hole, it automatically opens and a coke guide hopper is placed over the p hamber so the bucket and the charging hole are sealed. Automatic gates o n the bottom of the bucket and the red hot coke enters the prechamber. D this time, the pressure at the charging hole is between 0.02 and 0.03 i ater gauge. After the prechamber is charged, the coke guide hopper is r ed, the charging hole closes automatically, and the bucket is returned to t lectric locomotive. After 40-50 minutes, according to Linsky, the coke


HOIST
CLEANED COOLER GAS
COKE BUCKET
AUTOMATIC CHARGING COVER
FINE DUST CYCLONE
PRE CHAMBER
SUPER-HEATED STEAM 830°F 580 psi
COARSE DUST SEPARATOR
STANDARD STEAM BOILER
DRY QUENCH TOWER
COOLED GAS DISTRIBUTOR
WATER IN
COKE GATE
QUENCH AS FAN
TRANSPORT CAR
QUENCHED COKE CONVEYOR

SOURCE: Linsky (1978).

Figure IV-8. Schematic View of the Soviet Dry Quenching System

drops through the prechamber and begins to fall into the cooling zone. As the coke falls through the cooling zone, circulating gases cool the coke to between 400°F and 500°F.

Periodically, a discharge gate, which can be adjusted according to the required capacity of the cooling chamber, allows batches of coke to fall from the bottom of the cooling zone onto conveyors running under the quenching unit described above. Between 2 and 2-1/2 hours are required for the coke to pass through the quench unit and onto the conveyors.

The discharge gate, which is a double gas-tight structure, operates automatically and interlocks mechanically to ensure proper opening sequences. Approximately 100 seconds separate consecutive discharges of 1-1/2 to 2 tons. The maximum number of discharges possible per hour, as stated in the Linsky article, is 35 (average throughput 60 ton/hr). The Soviet system uses a blower to circulate the quenching gases through the "tower-boiler" system. To reach the cooling chamber, quenching gases are initially forced into distribution ducts, where they pass through peripheral slots and a central divider into the cooling chamber.

As the gases rise in the cooling chamber, heat is transferred from the hot coke to the circulating gases. After the gases are heated to between 1380°F and 1470°F, they pass from the cooling chamber into dust dropout chambers.

In the dust dropout chambers, coarse particulates are removed so that the boiler elements will be protected from erosion. Once the coarse particulates have been removed (200-400 lb/hr collected), the gases pass from the dust dropout chamber into the waste-heat boiler where they are cooled to between 350°F and 390°F and high-pressure steam is raised.

After cooling in the waste-heat boiler, the gases pass through two dust recovery cyclones. In the cyclones, finer particulates are removed so that the gas blower, which forces the gases through the dry quenching system, will be protected from erosion. (Particulates are collected here at a rate of 400-600 lb/hr.) Dusts removed from the circulating gases are periodically removed by pneumatic transport. They are mainly carbon dusts that can be burned as a solid fuel.

After the finer particulates are removed, nitrogen may be added to the gases so that their composition will meet operational safety regulations. Finally, the gases are sent to the blower to repeat the gas cycle. Instruments control the operations of cooling towers, charging and discharging coke, and monitor the temperature of the cooled coke, pressure and rate of circulating gas, and so forth.

3. Pollutant Emissions and Necessary Abatement

Figure IV-9 is a block diagram of the process showing potential pollutant emissions. Coke dust could be discharged to the ambient air since potential dust emission sources are located at points where the quenched coke is discharged onto the conveyor from the dry quenching unit, and also where coke dust is discharged from the dust dropout chamber and cyclone dust separators on to the conveyor belts that carry the dust to storage. The designs of dry quenching units considered in this study have provisions for hooding at coke/coke dust discharge points. Air collected at such points is being exhausted through a bag house, and the dust, mainly coke breeze, is collected in a dust hopper. It is likely to be used as a fuel on the plant site.

There is some potential for dust emission during coke transfer and coke charging to the dry quenching unit. However, according to discussions with American Waagner Biro, the transfer car and charging side of the unit can be designed so as to minimize such emissions.

There have been references in the literature (Linsky, 1975) concerning the addition of nitrogen to control the gas composition and to prevent the formation of an explosive CO-rich mixture. This would imply as well a bleed stream containing carbon monoxide and particulates.

The emissions during pushing operations are another matter. While we recognize that current design concepts claim a relationship between pushing emissions control and the type of track vehicle used to transport the incandescent coke, we believe that pushing emissions can be equally controlled in wet or dry quenching.

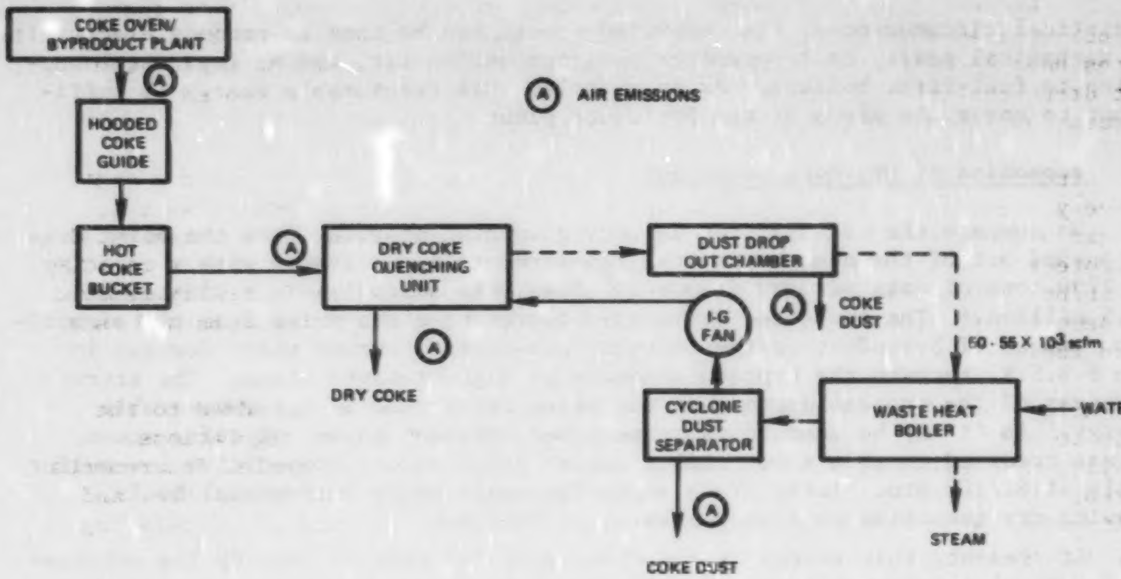

COKE OVEN/ BYPRODUCT PLANT
A
A AIR EMISSIONS
HOODED COKE GUIDE
HOT COKE BUCKET
A
DRY COKE QUENCHING UNIT
DUST DROP OUT CHAMBER
A
COKE DUST
I-G FAN
50 - 55 X 10³ scfm
A
DRY COKE
CYCLONE DUST SEPARATOR
WASTE HEAT BOILER
WATER
A
STEAM
COKE DUST

Figure IV-9. Block Diagram of Dry Quenching Indicating Potential for Pollutants

4. Technological Factors

Dry quenching is reported (Kemmetmueller, 1973) to yield a better quality of coke in comparison with wet quenching because of even cooling which results in more uniformly sized coke. Two percent increase in usable coke output per ton of coal charged has been reported, reflected by a similar reduction in coke breeze. Better mechanical strength, dryness of product, uniform distribution of volatile constituents, and less adhering breeze are said to contribute to smoother blast furnace operation with dry quenched coke. Moreover, in the Russian literature there are reports of decreases in coke rates of 2-3% in Soviet blast furnace trials with dry quenched coke. We have yet to come across any published data that will substantiate such claims for dry quenched coke using U.S. coking coals.

5. Energy Considerations

In wet quenching the sensible heat in the hot coke is lost to the water used in quenching. When the hot coke is cooled to 400°F in a dry quenching unit, about 1.1×10^6 Btu/ton of coke are recoverable.

Conceptually, the recovered energy can be put to a variety of uses. For instance, the 1.1×10^6 Btu/ton that dry quenching is capable of recovering is equivalent to about 940 lb of superheated steam. Under the right economic and logistical circumstances, the recovered energy can be used to produce electricity or mechanical power, or to preheat coal, combustion air, and/or feed water supplies to fuel-fired boilers. As an example, this recoverable energy is sufficient to cover the needs of the byproduct plant.

6. Economics of Dry Coke Quenching

We compare the costs of wet and dry quenching starting from the point coke is pushed out of the ovens. Capital requirements for a system with a capacity of 2750 tons of coke per day (1.0×10^6 tons coke annually) is estimated at \$9.5 million.* The projected savings in operating costs arise from the significant amount of byproduct energy recovery possible. Current plant designs in the U.S.S.R. recover the byproduct energy as high-pressure steam. The attractiveness of the process depends on the value attributed to the recoverable energy. As it may be used to generate power, preheat gases, or raise steam, it was credited in this study with a dollar value set by competitive low-sulfur fuels at $\$2/10^6$ Btu. Table IV-20 shows the costs on an incremental basis, viewing dry quenching as a mechanism to recover heat.

At present, this energy credit alone does not seem to justify the substantial capital investment involved. If, however, it can be demonstrated in U.S. blast furnace practice that dry quenching yields a better quality of coke so that the coke rate in the blast furnace is reduced, then there is likely to be a greater driving force for the adoption of the process. Further research is needed to establish this point.

TABLE IV-20

INCREMENTAL COSTS INCURRED BY A NEW DRY COKE QUENCHING UNIT

Annual Design Capacity: 1.0×10^6 tons
Capital Investment: (\$9.5 an annual ton)
Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	\$/Unit	Units Consumed per Ton of Product	\$/Ton of Product
VARIABLE COSTS				
● Electric Power Purchased	kWh	0.016	8.4	0.134
Energy Credits				
●	10^6 Btu	2.00	-1.1×10^6 Btu	-2.20
Direct Operating and Maintenance Labor (Wages)	L Man-hr	7.00	0.008	0.056
Direct Supervisory Wages	+S Man-hr	7.00	0.003	0.021
Maintenance Materials and Supplies	5% Investment			0.48
Labor Overhead	(35% L&S)			0.027
FIXED COST				
Plant Overhead	(65% L&S)			0.050
Local Taxes and Insurance	(2% Investment)			0.19
Depreciation				0.530
TOTAL PRODUCTION COSTS				0.712
RETURN ON INVESTMENT (PRETAX)				1.900
TOTAL				1.188

---

*Estimates supplied to us by AISI (1976) late in this study indicate these investments are probably low. This would have the effect of making dry quenching even a less favorable economic alternative than indicated in this study.

7. Current Adoption Status

Dry quenching was developed by the Sulzer Brothers shortly after World War I. Over 70 coke plants in gas works and some steel mills were equipped with dry coke quenching units up to 1950, but most of these gas-works installations were closed as low-cost natural gas became readily available. Only two of these are still in operation: one is in England at the Ford Dagenham plant; the other one is located at Wendel-Sidelor, Homecourt, France.

Linsky (1975) observed that, in 1960, the Soviet Union commissioned its first dry quenching pilot plant at Cherepovets Integrated Iron and Steel Works, north of Moscow. Because of its success in a relatively cold climate where wet quenching may be difficult, more than 40 dry quenching towers have been built in the Soviet Union which quenched approximately 15 million tons of coke in 1973. Apparently dry quenching facilities are mandatory in the U.S.S.R. for all new coke oven batteries as well as for rebuilt batteries if space permits.

We understand that in the U.S.S.R., with centralized planning, many of the steel facilities are quite large and produce more than 5 million tons of steel annually. Several dry quenching systems can be installed in an integrated facility. The reliability question is, therefore, not a critical issue. Barker (1976) reports that one Russian-designed installation is now operating in Japan at Nippon's Steel Tobata Works. Nippon Steel has reportedly filed 16 patent applications on modifications of the Russian design. Completion of another dry-quenching installation based on the Russian design is expected in 1977 at the Chiba Works of Kawatetsu Chemical Industry in Japan.

Two designs, both of which are based on the old Sulzer patent, are presently offered to U.S. steelmakers. One is offered by Licenzintorg (U.S.S.R.) and the other one is offered by Waagner Biro, an Austrian firm which acquired the patent from Sulzer in 1971.

There is probably little future for dry quenching with coke ovens that produce in the order of 1,000,000 tons a year. For such facilities only one dry quenching station is needed, and the reliability issue then becomes critical. Our discussions with steelmakers that have seen dry quench facilities in the Soviet Union indicate that they would have real concerns about installing such a facility without a backup to quench the coke. Without such a backup and with the failure of a fairly complex system, such as a dry quenching facility is reported to be, the complete steel facility would be in danger of closing for lack of coke. It would then take several weeks, even months, to bring production back into line. Thus prudent business practice would call for a backup quench facility, and the lowest cost backup that is currently available and that would meet current environmental regulations would be a wet quench tower. Thus the U.S. steelmakers look upon dry quenching for many of their applications as equipment that has to be installed in addition to their wet quench system. For this reason, we have figured the costs on an incremental basis and looked upon the dry quenching system as a mechanism to recover heat.

For larger steel facilities, those producing 5,000,000 or more tons of steel a year where multiple dry quenching towers would be needed, one could, of course, eliminate the wet quench backup system. In such an instance, one might be able to save about 10% of the estimated cost of $25 to $30 million for three dry quench systems. Therefore, the applications for dry quenching seem to be in large steel plants which will be undoubtedly re-examining on a periodic basis the dry quenching option in the face of changing economic conditions such as energy costs and dry quench facility investments.

E. DIRECT REDUCTION

The blast furnace is now - and will remain for decades to come - the primary way of reducing iron ores, if only because most existing units are far from the end of their useful lives. However, oxygen has been successfully removed from solid iron oxides by gaseous reduction in a number of instances.

Traditionally, direct reduction units have been considered only where special conditions have made them appear economically attractive as an alternative to the blast furnace (small production, unavailability of coke, special incentives, etc.). The economic situation of industrialized countries is such that the treatment of metallized ores in electric furnaces or in blast furnaces may become an alternative to the conventional blast furnace practice.

Several processes, as shown in Table IV-21, have been proposed. Although most of them have not been commercialized, a few are presently receiving considerable attention in North America and in other parts of the world. For example:

- fluidized-bed direct reduction (FIOR process),
- static bed process (HyL process),
- shaft furnace (moving bed) processes (MIDREX, Armco), and
- kiln-type processes (SL/RN*, Krupp, Kawasaki).

The first three processes require a gaseous reductant, while the kiln processes generally operate with a solid fuel (coal) supplemented by liquid or gaseous fuel injection. For the gaseous reduction processes, the reducing gas normally has been generated from natural gas and occasionally from naphtha. The shortages of these types of feedstocks cast some doubt about whether such a gas-based process can be built in the United States.

Alternatively, heavier petroleum feedstocks or coal could be gasified and the resultant gases, if of the proper quality, can be used in direct reduction. Unfortunately, with such feedstocks, a considerable amount of sulfur usually enters into the reducing gas stream, normally as H_2S or COS. To utilize these gases in direct reduction, the sulfur-containing species would

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*SL/RN comes from the name of the companies who developed this process; Stelco-Lurgi/Republic Steel, National Lead.

TABLE IV-21

CLASSIFICATION OF DIRECT-REDUCTION PROCESSES

1. PROCESSES USING SOLID REDUCTANTS

Kiln Processes
Krupp-Renn
R-N, SL-RN
Bassett
Sturzelberg
Domnarfvet
Hornsey-Wills

Retort Processes
Hoganas
Chenot
Larkins
DuPuy
Lang

Electric-Furnace Smelting Processes
Tysland-Hole
Lubatti
Elektrometall
D. L. M. (Dwight-Lloyd-McWane)
Strategic-Udy
Edwin-Elektrokemisk

Low-Shaft Blast-Furnace Processes
Ougree-Liege
Demag-Humboldt
Weber

Miscellaneous Solid-Reductant Process
Rudolph-Landin
Leckie
Gerhardt

2. PROCESSES USING GASEOUS REDUCTANTS

Kiln Processes
Maier-Mococo
Azincourt
Scortecci

Shaft-Furnace Processes
Wiberg-Soderfors
Norsk-Staal
U. S. Bureau of Mines
Skinner Multiple-Hearth
Cape-Brassert
United Verde
Norwegian H-Iron
Galluser
Purofer
Armco Steel
Midland-Ross

Fluidized-Bed Processes
Nu-Iron
H-Iron
A. D. L. (Esso Research-Little)
Stalling
Bubble-Hearth
Novalfer-Ouia

Retort Processes
Madaras-Mexican
Hyl

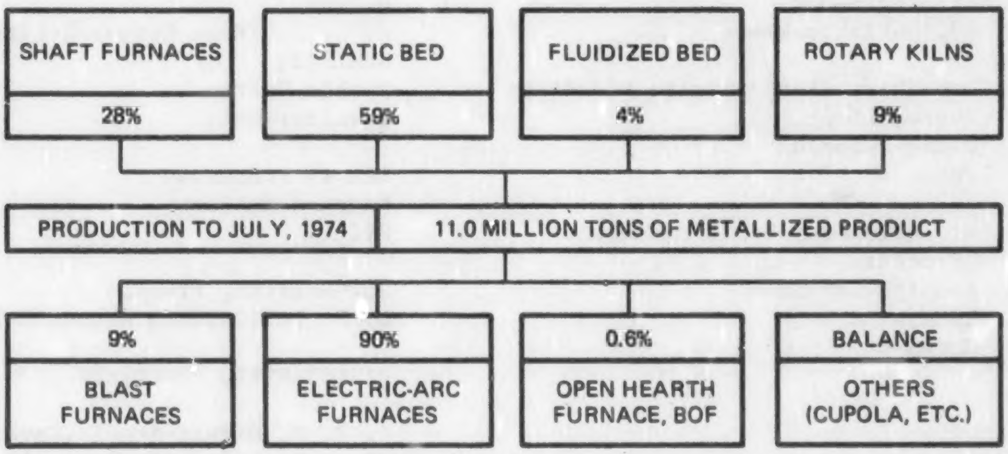
Jet-Smelting Process
O. R. F. (Ontario Research Foundation)

DIRECT-STEEL PROCESSES

O. R. F. Direct-Steel (Cavanagh)
Flame-Smelting (Cyclosteel)
Twyman

Source: Making, Shaping and Treating of Steel, U.S. Steel Corp., Pittsburgh, Pa., 1971 have to be scrubbed out. At present, there are no economical high-temperature (1500-2000°F), sulfur-removal processes. If the gases have to be cooled in order to scrub out the sulfur-containing species and then reheated, energy costs and capital investments make such an alternative economically unattractive. For this reason we have focused here on the last alternative, namely, the coal-based kiln processes, most of which use limestone, if necessary, for sulfur control.

Since large plants have been - and are being - built using the SL/RN process, we have used this particular process as the basis for out analysis. Because 90 percent of the metallized products from direct reduction units is charged to electric furnaces, as shown in Figure IV-10, we have chosen the use of direct reduced material in electric arc furnaces (EAF) rather than using direct reduced product in a blast furnace followed by the BOP for steelmaking. As stated earlier, we have retained, for the base line technology, the conventional coke oven-blast furnace-basic oxygen process. A schematic flowchart of the base line is shown on Figure IV-11 with the alternative direct reduction-electric arc furnace route shown on Figure IV-12. Examination of Figures IV-11 and IV-12 for the base line and alternative processes shows both using oxide pellets to produce an equivalent end-product, namely 1,710,000 tons of molten steel per year, as shown in Table IV-22.


SHAFT FURNACES
28%
STATIC BED
59%
FLUIDIZED BED
4%
ROTARY KILNS
9%
PRODUCTION TO JULY, 1974
11.0 MILLION TONS OF METALLIZED PRODUCT
9%
BLAST FURNACES
90%
ELECTRIC-ARC FURNACES
0.6%
OPEN HEARTH FURNACE, BOF
BALANCE
OTHERS (CUPOLA, ETC.)

Source: Rollinger, B., "Steel via Direct Reduction," Electric Furnace Proceedings, Vol. 32., p. 5, Pittsburgh, 1974

Figure IV-10. Production and Processing of Metallized Product, July 1974

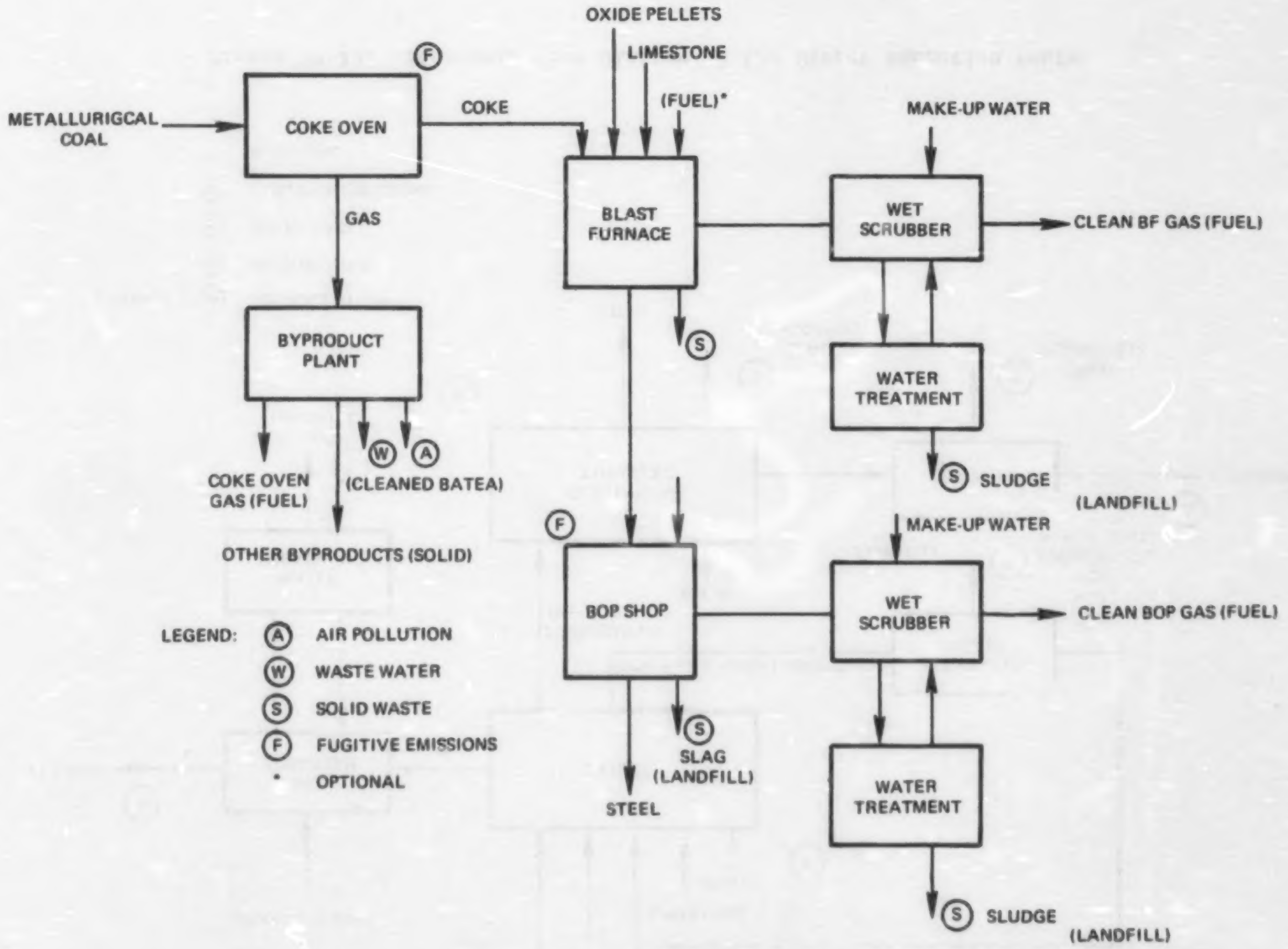

OXIDE PELLETS
LIMESTONE
(FUEL)*
F
METALLURIGCAL COAL
COKE OVEN
COKE
MAKE-UP WATER
GAS
BLAST FURNACE
WET SCRUBBER
CLEAN BF GAS (FUEL)
BYPRODUCT PLANT
S
WATER TREATMENT
W
A
COKE OVEN GAS (FUEL)
(CLEANED BATEA)
S
SLUDGE
(LANDFILL)
F
MAKE-UP WATER
OTHER BYPRODUCTS (SOLID)
BOP SHOP
WET SCRUBBER
CLEAN BOP GAS (FUEL)
LEGEND:
A AIR POLLUTION
W WASTE WATER
S SOLID WASTE
F FUGITIVE EMISSIONS
* OPTIONAL
S
SLAG (LANDFILL)
STEEL
WATER TREATMENT
S
SLUDGE
(LANDFILL)

Figure IV-11. Schematic Flow Diagram of the Base Line Process for Steelmaking

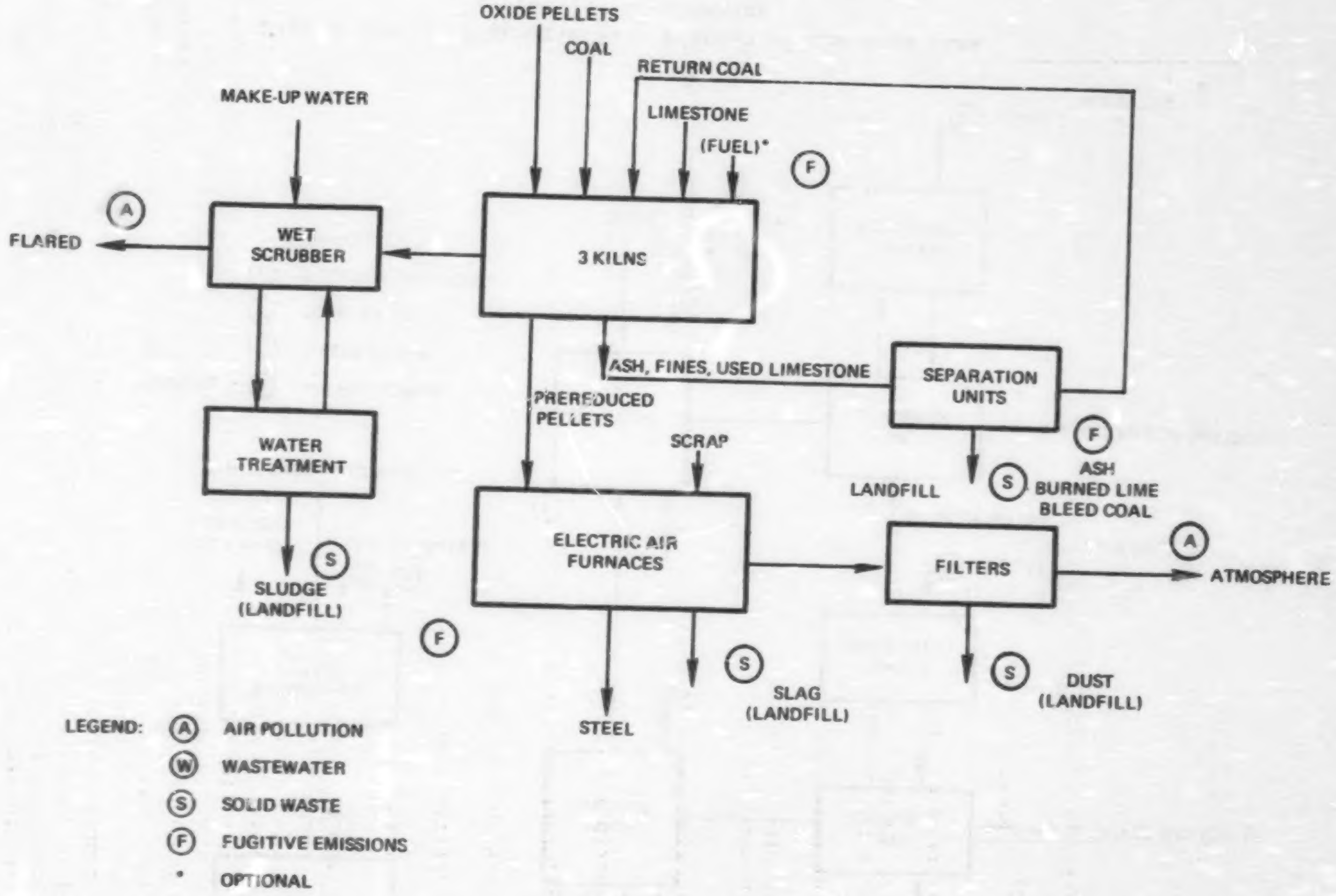

OXIDE PELLETS
COAL
RETURN COAL
LIMESTONE
(FUEL)*
MAKE-UP WATER
F
A
FLARED
WET SCRUBBER
3 KILNS
ASH, FINES, USED LIMESTONE
SEPARATION UNITS
PREREDUCED PELLETS
WATER TREATMENT
SCRAP
F
ASH
BURNED LIME
BLEED COAL
LANDFILL
S
ELECTRIC AIR FURNACES
FILTERS
A
ATMOSPHERE
S
SLUDGE (LANDFILL)
F
S
SLAG (LANDFILL)
S
DUST (LANDFILL)
STEEL
LEGEND:
A AIR POLLUTION
W WASTEWATER
S SOLID WASTE
F FUGITIVE EMISSIONS
* OPTIONAL

Figure IV-12. Schematic Flow Diagram of the Direct Reduction Route

TABLE IV-22

DEFINITION OF THE BASE LINE AND PROCESS OPTION CONSIDERED FOR DIRECT REDUCTION

Base Line			Process Option		
Process Step	Product	Capacity (annual tons product)	Process Step	Product	Capacity (annual tons product)
Coke Oven	Coke	660,000			
Blast Furnace	Hot Metal	1,200,000	DR Plant (3)	Reduced Pellets	1,200,000
BOP Shop (2)	Steel	1,710,000	EAF Shop (2)	Steel	1,710,000

EAF = Electric Arc Furnace

NOTE 1: The coke consumption of the blast furnace is 1,100 lb/ton of hot metal.

NOTE 2: Both routes use 30% scrap in their steelmaking vessels.

NOTE 3: The direct reduction plant consists of three SL/RN units having an annual capacity of 400,000 tons each.

The following pages on direct reduction are broken down into four main sections:

1. Description of the direct reduction route to steelmaking.
2. Pollutant emissions, abatement technology, and costs.
3. Energy use of the two process routes to steelmaking.
4. Investments and operating costs.

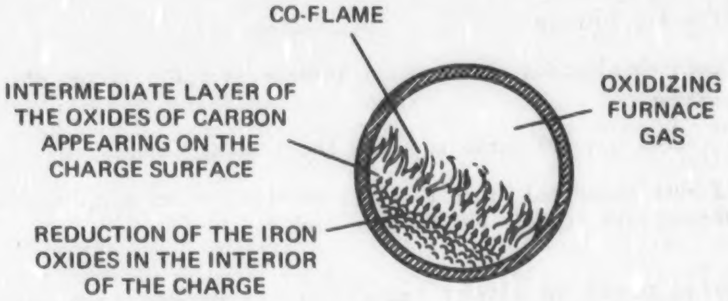
1. The Direct Reduction Route

a. Description of the SL/RN Process

Each existing plant is unique in its design and application; however, Figure IV-12 shows a typical flow sheet for the treatment of high-grade pellets or lump ore and solid reductants with a low content of volatile matter. Iron oxides, coal, and lime for desulfurizing are mixed and charged into a rotary kiln. Coal provides the reducing gas (CO) and the sensible heat for the reduction of iron oxides. Air is admitted at the lower end of the kiln and, through several blowers, is distributed along the length of the kiln. Supplementary fuel can be supplied by oil burners. The temperature, measured by thermocouples, is regulated to around 1922°F by the air and fuel rates. The spent gases exit at the charging end of the kiln at about 1200°F. It is therefore a countercurrent process, although other units have been designed as concurrent reactors.

Theoretically, a wide variety of charge characteristics is acceptable; lump ore, green balls, indurated pellets, and even wet concentrates have been considered. The acid gangue content, however, should be less than 2-4% so that the product will be acceptable as feedstock for a blast furnace or electric arc furnace. Also, any reductant is acceptable as long as the ash does not fuse or form low-melting compounds with other species present, such as the desulfurizing agent and the gangue coming with the iron oxides. The softening point of the coal should be at least 210°F above the maximum temperature in the kiln. Thus, the type of coal has an important bearing on the successful operation of the kiln.

Figure IV-13 shows a section of the kiln in the reducing zone. The rotary movement facilitates the heat and mass transfers. The product is highly metallized; that is, 93-95% of the total iron is present as metal.


CO-FLAME
INTERMEDIATE LAYER OF THE OXIDES OF CARBON APPEARING ON THE CHARGE SURFACE
OXIDIZING FURNACE GAS
REDUCTION OF THE IRON OXIDES IN THE INTERIOR OF THE CHARGE

Source: Johannsen, quoted in L.v. Bogdandy and H.J. Engell, "The Reduction of Iron Ore," Springer Verlag, Berlin, 1971.

Figure IV-13. The Reduction Zone of the SL/RN Process

After the reduction has taken place, the products pass into a cooling drum where they are cooled to below 210°F to prevent reoxidation. The cooler discharge, consisting of coarse- and fine-grain sponge-iron excess coal, coal ash and desulfurizing agents, is split into the individual components by screening and magnetic separation. They may also be separated by electrostatic separation, flotation, and air jig. At times, difficulty has been experienced in separating the coal from the ash; extreme care and skill must be used to avoid either excessive coal usage or excessive ash buildup. The unburned or excess coal is largely recycled.

If pellets are fed the metallized products are produced in the form of pellets along with some fines. The pellets are not pyrophoric and they do not reoxidize, so long as they are not brought into contact with condensed water. Moreover, any excessive air draft through a pile of prereduced pellets should be avoided. If a steelmaking plant is adjacent to the kiln, the fines and pellets can be charged continuously. If the product has to be shipped, the fines must be briquetted or otherwise agglomerated, which increases their cost.

b. Uses for Prereduced Materials in Iron and Steelmaking

Prereduced materials are an intermediate product since they cannot be thought of as either an ore or a metal in the common sense. They are being considered today as a feedstock to both blast furnaces and electric furnaces.

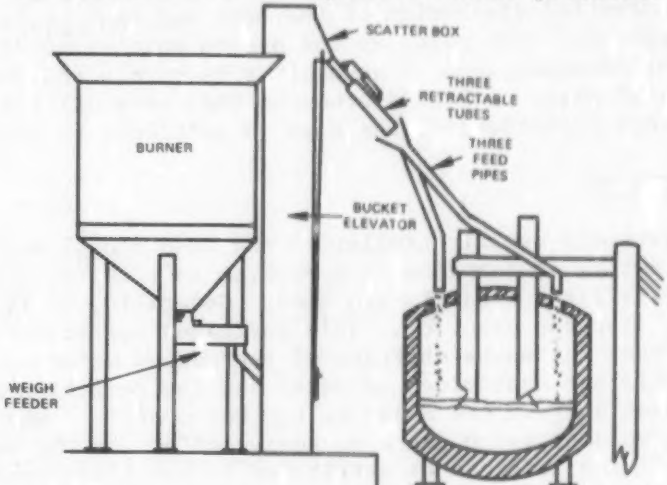
(1) Use in Electric Arc Furnaces

Ninety percent of the prereduced materials produced in the world is fed to electric arc furnaces (EAF). Although the operating conditions vary significantly from plant to plant (composition of the feedstock, capacity, power, charging method, end-product), one may characterize the process as follows.

The EAF usually melts scrap (home and/or purchased) together with the prereduced materials. Whereas the roof must be open in order to charge scrap, the prereduced materials are more often charged continuously (Figure IV-14). With direct reduced materials, coke is often used and three pounds of limestone are added for each pound of silica contained in the prereduced materials to operate the EAF under normal basic conditions.

The utilization of prereduced materials has a good potential for minor element control. Elements that tend to build up in steel because of scrap recirculation (Cu, Ni, Cr, Sn) undergo some dilution. The phosphorus content depends largely on the ore quality, because direct reduction processes are not likely to remove it in significant proportions. The sulfur content depends on the ore quality and the reduction practice. Should the sponge iron be sufficiently low in sulfur and phosphorus, either lower grades of scrap could be used in conjunction with prereduced materials or the refining period could be shortened.

In conclusion, EAF's of traditional design can accommodate prereduced materials with no limitation on the grade of steel produced.



SOURCE: Lurgi Publication No. 166

Figure IV-14. Example of Continuous Charging System

(2) Use in Blast Furnaces

Ten percent of the prereduced iron units produced in the world is charged to blast furnaces.

As shown in Figures IV-15 and IV-16, coke consumption decreases by 0.5% and the production increases by 0.7% with each percent of burden metallization. The production of a blast furnace plant with an annual capacity of 2 million tons of pig iron, for example, can be raised by 25% to 2.5 million tons by premetallizing the burden to approximately 35%. A sponge-iron plant with an annual capacity of about 1 million tons would be needed to achieve the same increase with equal ores.

Should prereduced materials become available on the U.S. market, some flexibility in blast furnace productivity could be gained. However, they would probably introduce no new pollution control problems around the blast furnace. Thus, for purposes of this study, we focused on the direct reduction/electric furnace route to steelmaking and compared it to the conventional coke oven-blast furnace-basic oxygen process.

c. Technological Problems

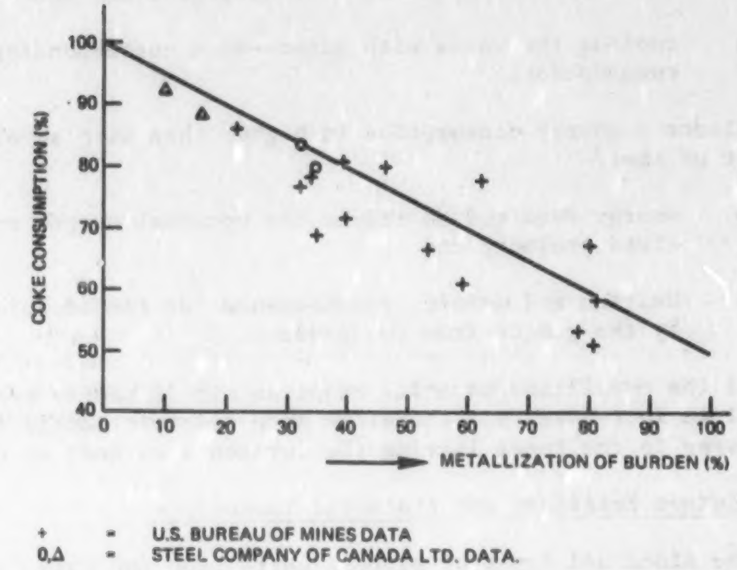
(1) The SL/RN Process

Although it may seem a relatively simple device, a rotary kiln is very difficult to operate. Some attrition of the charge is bound to occur. Furthermore, the dust particles tend to overheat and sinter in "dam rings" against the shell of the furnace. These rings slowly build up to the point of completely obstructing the furnace, forcing a complete shutdown of the operations.

The control of the temperature profile in the kiln is complex and critical. Without going into a detailed discussion of the heat and mass transfers involved, one must emphasize this point as the one on which extensive R&D is still proceeding. The reaction zone is actually very narrow and non-uniform, so that the formation of pasty or liquid products that eventually solidify on colder regions and force a shutdown of the kiln is difficult to avoid.

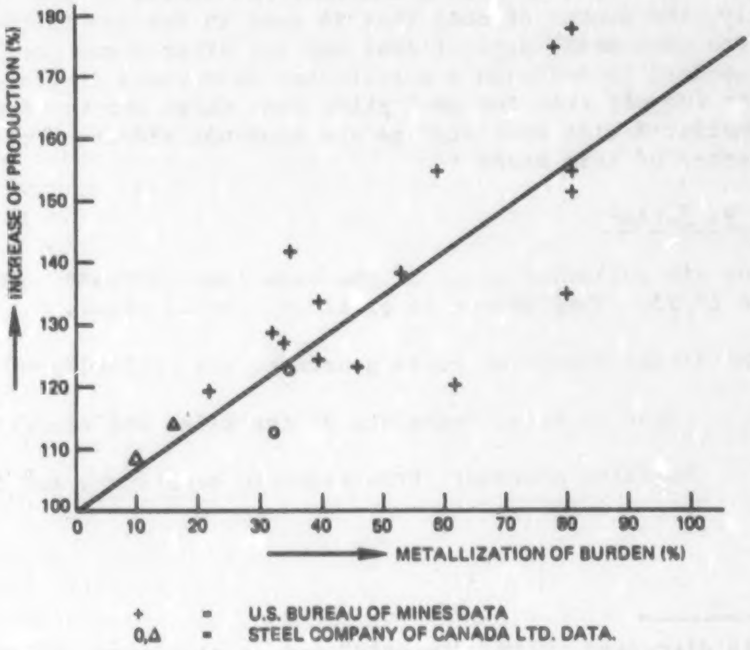
(2) Electric Arc Furnaces

These process units are usually similar to the traditional scrap melting units. However, refractory consumption is a problem in electric arc furnace operations in which metallized products are used. Generally, it is 20 to 60% higher than that for all-scrap practice. This increased refractory consumption results principally from continuous charging of prereduced material with full power; the furnace walls are unshielded by scrap and the radiation of the arc damages the walls, especially in the areas of the hot spots. A second factor is the increased slag volume, which has a corrosive effect on the walls. The decrease in the roof-lining life can be attributed to the fines generated during handling and charging of the sponge iron. These fines penetrate the refractories and form low-melting eutectics. These problems are partially controlled by --



SOURCE: USBM and Lurgi, Publication No. 166

Figure IV-15. Decrease of Coke Consumption by Charging Prereduced Burden into the Blast Furnace



SOURCE: USBM and Lurgi, Publication No. 166

Figure IV-16. Increase of Blast Furnace Production by Charging Prereduced Burden

- shielding the walls with unmelted scrap as much as possible;
- utilizing special refractory material in the area of the hot spots, with the corresponding cost differential; and
- cooling the walls with water--with corresponding increase in energy consumption.

Electric energy consumption is higher than with an all-scrap practice as a result of the:

- energy required to reduce the residual oxygen content of the metallized product; and
- heating and melting requirements for the additional slag generated by the gangue from the product.

If the metallized material requires significantly more lime, the total slag volume increases, and therefore more electric energy is used. Additional heat losses in the fumes leaving the furnace also must be compensated for.

2. Pollutant Emissions and Abatement Technology

The sizes and types of process units used for this evaluation are those previously mentioned (Table IV-22). We anticipate no pollutional difference due to the pellets between the two alternative technologies being considered here. In both cases, we anticipate that there will be fugitive emissions and dusting from the pellets being unloaded and stored on the steel mill grounds. Similarly, the amount of coal that is used in the two technologies is about the same. One uses metallurgical coal and the other steam coal, but we have come across no data to indicate a significant difference in the dusting problems and water run-off from the coal piles from these two types of coals. The problems associated with coal storage are thus not addressed within the iron and steel sector of this study.*

a. Air Pollution

The air pollution costs of the base line (BATEA** technology) are shown in Table IV-23. They amount to $2.62 per ton of steel.

The direct reduction route generates air pollution of the following types:

- Point sources: exhausts of the kilns and electric furnaces; and
- Fugitive sources: from magnetic separators and transfer operations.

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*This is discussed in the "Ammonia" report also prepared under this contract (Chapter IV, "Ammonia Production" based on Coal Gasification).

**BATEA = Best Available Technology Economically Achievable.

TABLE IV-23

AIR POLLUTION CONTROL FOR BASE CASE
(Basis: 1.2 million ton/yr Iron)

Capital Cost, $		
Blast Furnace		-0-
Coke Oven		6,411,000
Basic Oxygen Furnace		4,669,000
Total		11,080,000
Operating Cost, $/ton		
Variable Costs		
Labor (total)		0.07
Maintenance @ 5% of Capital		0.46
Utilities		
Electric Power @ \$0.016/kWh		0.53
Water @ \$0.20/10^3 gal		0.13
Total		1.19
Fixed Costs, $/ton		
Depreciation, 18 years		0.51
Insurance & Taxes @ 2%, Capital		0.18
Total		0.70
Total Production Cost, $/ton		1.89
Return on Investments (pre-tax) @ 20%		1.85
Total Unit Cost, $/ton	$	3.74/ ton hot metal or
	$	2.62/ton steel

The gas flow rate from each kiln is estimated to be 57,000 scfm at 1200°F with a composition of 64% N_2, 2% CO_2, and 34% CO. In addition, SO_2, in a very low concentration, will be present in the gases arising from the fuel's sulfur content and from the ore. The estimated particulate loading will be 0.95 lb/ton of product. The chemical nature of the particles is Fe, Fe_3O_4, C, SiO_2, ash, CaO, and tramp elements. The large particulates in the exhaust will be removed in the cyclone and recycled. The smaller particulates including some submicron particulates will be removed using a high-energy venturi scrubber. The exhaust from the scrubber is a clean gas which can be flared. Lurgi (Dec., 1975) has claimed that the off-gases have a supplemental fuel value of 70 Btu/scf, but this depends on operating practice and cannot be generalized. It may be even lower.

The electric arc furnace exhausts are not significantly different from those of conventional units, except that their dust load may be 10 - 20% higher. Electrostatic precipitators will be installed and should suffice.

Table IV-24 summarizes the air pollution costs of the direct reduction plant and Table IV-25 for the electric furnaces. For a fair comparison of the two routes, it must be remembered that the gas-cleaning devices of the blast furnace are considered process equipment, because they continuously deliver blast furnace gas (80-90 Btu/scf) to the stoves and other facilities. Therefore, they do not appear as a pollution control device.

TABLE IV-24

AIR POLLUTION COSTS FOR THREE DIRECT REDUCTION KILNS
(Basis: 1,200,000 ton/yr)

Capital Cost:	$ 5,658,000	
Operating Costs:		
Variable Costs:		$
Electric Power @ $0.016/kWh		95,400
Water @ $0.20/$10^3$ gal		17,100
Direct Labor (L)		7,565
Supervision (S) @ 15%/L		1,135
Labor Overhead @ 35% (L&S)		3,045
Maintenance @ 4% of Investment		226,320
Total Variable Costs		350,566
Fixed Costs:		
Plant Overhead @ 65% (L&S)		5,635
Local Taxes & Insurance @ 2% of investment		113,160
Depreciation (18 years)		314,333
Total Fixed Costs		433,148
Total Variable and Fixed Costs		783,713
ROI 20% of Investment (pre-tax)		1,131,600
Total		$ 1,915,313
UNIT COST		$1.59/ton of sponge iron.

TABLE IV-25

AIR POLLUTION CONTROL COSTS FOR AN ELECTRIC ARC FURNACE SHOP
(1,710,000 ton/yr)

CAPITAL INVESTMENT (CI): $5.6 million

Operating Costs	Unit	$/Unit	Units/ 10^6 SCF	Annual Cost ($)
Variable Costs:				
Electric Power	kWh	0.016	46.4	380,724
Direct Labor and Maint. L	man-hr	7.00	0.15	551,880
Direct Supervisory Wages	15%L			82,782
Maintenance Materials	4%	Invest		224,000
Labor Overhead	35%	(L&S)		222,131
Miscellaneous				150,000
Total Variable Costs				$ 1,611,517
Fixed Costs				
Plant Overhead	65%	(L&S)		412,530
Local Taxes & Insurance	2%	(CI)		112,000
Depreciation, 18 years				313,600
Total Fixed and Operating Costs				2,449,647
ROI (pre-tax)	20%	(CI)		1,120,000
TOTAL				$ 3,569,647
UNIT COST				$2.09/ton of steel

Table IV-26 shows that the cost of air pollution control in the direct reduction route is \$3.21/ton of steel.

TABLE IV-26

TOTAL AIR POLLUTION COST FOR THE DIRECT REDUCTION ROUTE

	\$/ton Steel
DR Kiln Air Control:	\$1.12(1)
EAF Air Control:	2.09
Total	\$3.21/ton steel

b. Effluent Wastewater

(1) The Base Case

As previously discussed, the base case consists of a byproduct coke oven, a blast furnace, and a basic oxygen furnace shop, all of which generate wastewater streams. Wastewaters from byproduct coke operations contain high concentrations of ammonia, oil and grease, and phenol (all three of which exert a biochemical oxygen demand), plus cyanide, sulfide, and suspended solids. Wastewater characteristics of blast furnace scrubber water have been described in the discussion of the direct-reduction alternative. The basic oxygen furnace generates a wastewater containing suspended solids and fluorides. The three treatment systems chosen in the EPA Development Document (1974) for the attainment of the BATEA treatment levels have been used in estimating the capabilities and costs of treatment. These treatment systems are:

- Byproduct Coke

    1) Distillation (with ammonia recovery) of waste ammonia liquor,

    2) Alkaline ammonia stripping,

    3) Neutralization,

    4) Settling,

    5) Air flotation,

    6) Two-stage chlorination,

    7) Clarification (with vacuum filtration of sludge),

    8) Filtration, and

    9) Carbon adsorption:

---

(1) The feed to the EAF is a mix of sponge iron and scrap.

- Blast Furnace

  (See direct reduction discussion); and

- Basic Oxygen Furnace

  1) Clarification (97% recycle of effluent),

  2) Neutralization,

  3) Lime precipitation,

  4) Clarification (with vacuum filtration of sludge), and

  5) Final neutralization.

An estimate of the treated effluent characteristics is presented in Table IV-27. Column D of Table IV-27 lists the total treated effluent waste load for the entire base case.

(2) Direct Reduction Alternative

There is one significant wastewater stream from the direct reduction process: the kiln exhaust gas scrubber water. (The direct reduction process requires non-contact cooling water at the rate of about 4,000 gal/ton of iron, but this water is comparable in volume and composition to that of the blast furnace it replaces, and thus will not be included in the comparison.)

The exact composition of the kiln exhaust gas is not known. In view of the chemistry of this process, the exhaust gas and its associated scrubber water should be similar to that of a conventional blast furnace. The composition of blast furnace scrubber water has been established reasonably well. The major pollutants of concern in blast furnace scrubber water are:

- suspended solids,
- cyanide,
- phenol,
- ammonia,
- sulfide, and
- fluoride.

Due to the reducing atmosphere in the solid bed in the reduction kiln and the abundance of carbon, nitrogen, and sulfur in the coal, it is reasonable to expect that the exhaust gas scrubber water will contain cyanide, phenol, ammonia, and sulfide. Since no fluorspar fluxing agent is used in the direct reduction process, there would not normally be any fluoride in the exhaust gas scrubber water. This is an important environmental advantage of the direct reduction process over the base case.*

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*If fluorspar appears in the raw materials (limestone or coal), fluorides can be expected in the exhaust gases and the scrubber water is treated accordingly.

TABLE IV-27

BASE CASE TREATED EFFLUENT WASTE LOAD

Basis: Coke Oven - 660,000 ton/yr
Blast Furnace -1,200,000 ton/yr
Basic Oxygen Furnace-1,710,000 ton/yr

	A		B		C		D
	Treated Byproduct Coke Oven Effluent		Treated Blast Furnace Effluent		Treated Basic Oxygen Furnace Effluent		Total Treated Effluent Waste Load
Parameters	(lb/day	(mg/l)	(lb/day)	(mg/l)	(lb/day)	(mg/l)	(lb/day)
Suspended Solids	15.1	10	34.3	10	48.8	25	98.2
BOD_5	30.2	20	-	NIL	-	-	30.2
Oil & Grease	15.1	10	-	NIL	0	0	15.1
Cyanide$^{(2)}$	0.38	0.25	0.86	0.25	-	-	1.24
Phenol	0.75	0.5	1.72	0.5	-	-	2.47
Ammonia (as NH_3)	15.1	10	34.3	10	-	-	49.4
Sulfide	0.45	0.3	1.0	0.3	-	-	1.45
Fluoride	-	-	68.6	20	39.1	20	107.7
Flow Rate	180,800 gpd		411,000 gpd		234,000 gpd		825,800 gpd

Notes: 1) All effluents are subjected to "Best Available Technology Economically Achievable" (1983).

2) Cyanide is amenable to alkaline chlorination.

Since the wastewater from the direct reduction process is expected to be similar to blast furnace wastewater, it is reasonable to expect that the direct reduction scrubber water will have to be subjected to the same treatment as blast furnace scrubber water. The BATEA (Best Available Technology Economically Achievable) treatment level, to be implemented by 1983, is envisioned to require the following treatment steps:

- Clarification of the once-through scrubber water with vacuum filtration of the solids;
- Cooling and recycling (upwards of 97%) of the clarifier effluent; and
- Treatment of the recycle loop blowdown by
    1) alkaline chlorination,
    2) neutralization,
    3) clarification,
    4) filtration, and
    5) carbon adsorption.

Each direct-reduction kiln, with an estimated exhaust gas flow rate of 57,000 scfm, is equivalent (in terms of gas volume) to a blast furnace having a capacity of 1,296 ton/day. Application of the BATEA treatment level is expected to result in a treated effluent wastewater discharge of 125 gal/ton, or 162,000 gpd. Based on the expected effluent concentrations set forth in the EPA Iron and Steel Development Document, (1974), Table IV-28 presents an estimation of the treated effluent wastewater load from the direct reduction process. Table IV-29 summarizes the comparison of the two routes.

TABLE IV-28

DIRECT REDUCTION TREATED WASTEWATER LOAD
(Basis: 1,200,000 ton/yr)

Parameter	Treated Effluent Concentration (mg/l)	Treated Effluent Waste Load (lb/ton)
Suspended Solids	10	58.5
BOD_5	NIL	-
Oil & Grease	NIL	-
Cyanide	0.25	1.02
Phenol	0.50	2.04
Ammonia	10	57.15
Sulfide	0.3	1.23
Fluoride	Not Present	
Flow Rate	486,000 gpd	

Remarks:

1) Direct reduction-treated effluent is expected to be very nearly the same as the treated effluent from a blast furnace.
2) Direct reduction kiln scrubber water is subjected to "Best Available Technology Economically Achievable" (1983) specified for blast furnace scrubber water.
3) Cyanide amenable for alkaline chlorination.

TABLE IV-29

DIRECT REDUCTION COMPARISON OF TREATED WASTEWATER[1] LOADS

	A	B
Parameter	Total Base Case Treated Effluent (Based on: 1,200,000-ton/day Blast Furnace Capacity) (lb/day)	Direct Reduction Treated Effluent (Based on 1,200,000-ton/day [3 kilns] capacity) (lb/day)
Suspended Solids	98.2	98.2
BOD_5	30.2	nil
Oil & Grease	15.1	nil
Cyanide(2)	1.24	1.24
Phenol	2.47	2.04
Ammonia	49.4	58.5
Sulfide	1.45	1.45
Fluoride	107.1	NIL
Flow Rate	825,800 gpd	486,000 gpd

NOTES: 1) All treated effluents are subjected to the "Best Available Technology Economically Achievable" (1983).

2) Cyanide amenable to alkaline chlorination.

(3) Wastewater Treatment Costs

Wastewater treatment cost estimates for attaining the BATEA treatment level have been developed for both the base case and the direct-reduction alternative. The base case cost estimates are presented in Table IV-30, the direct-reduction cost estimates in Table IV-31, and the comparison of the two in Table IV-32.

As can be seen from the comparison presented in Table IV-32, the direct-reduction alternative has a unit treatment cost that is approximately 54% of the base case. Most of the reduction in cost is due to the absence of the wastewater-generating coke oven and BOP alternative.

c. Solid Waste Disposal

(1) Base Case

Each of the production units within the base case produces large volumes of solid waste, which are:

- Byproduct Coke - Solid wastes include coke dust and wastewater treatment sludge;
- Blast Furnace - Solid wastes include furnace slag and wastewater treatment sludge; and
- Basic Oxygen Furnace - Solid wastes include furnace slag and wastewater treatment sludge.

Estimated quantities and disposal costs are presented below:

Parameter	Yearly Quantity (ton/yr)	Total Yearly Disposal Cost(1) ($/yr)	Unit Disposal Cost(2) ($/ton output)
Byproduct Coke	13,200	66,000	0.04
Blast Furnace	240,000	1,200,000	0.70
Basic Oxygen Furnace	256,500	1,282,500	0.75
TOTAL SOLID WASTE	509,700	$2,548,500	$1.49/ton steel

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(1) Disposal cost @ $5.00 per actual ton.
(2) Based on 1,710,000 ton of steel/year.

TABLE IV-10

BASE CASE WASTEWATER TREATMENT COSTS
(Basis: 1,200,000 ton of Hot Metal/yr)

CAPITAL INVESTMENT - $18,700,000

	Annual Quantity	Cost per Unit Quantity	Quantity per Ton of Product	$ per Ton of Hot Metal
VARIABLE COSTS				
Operating Labor (L)	84,000 hr	$ 7.00/man-hr	0.07	0.49
Supervision (S)	15% (L)			0.07
Labor Overhead	35% (L+S)			0.20
Maintenance (Labor + Materials)	-	-	-	0.77
Chemicals includes: • lime • chloride • acid • activated carbon	-	-	-	0.26
Electrical Power	12,700,000 kWh	$0.016/kWh	10.62	0.17
Fuel	435,600 x 10^6 Btu	$2.00/$10^6$ Btu	0.363	0.73
TOTAL VARIABLE COST				2.68
FIXED COST				
Plant Overhead	65% (L+S)			0.36
Taxes & Insurance	- 2% CI	-	-	0.31
Depreciation (@ 5.6%)	18 years	-	-	0.87
TOTAL FIXED COST				1.54
TOTAL ANNUAL COST				4.22
RETURN ON INVESTMENT 20% CI				3.12
TOTAL				$7.34/ton hot metal or $5.15/ton steel

NOTES:
1) Base Case includes byproduct coke, blast furnace, and basic oxygen furnace.
2) Cost estimates are for the ground-up implementation of the "Best Available Technology Economically Achievable" treatment level (1983).
3) Cost does not include wastewater treatment sludge disposal. However, this cost is included in the discussion of solid waste disposal.

TABLE IV-31

DIRECT REDUCTION KILN SCRUBBER WASTEWATER TREATMENT COSTS
(Basis: 1,200,000 ton of sponge iron/yr)

CAPITAL INVESTMENT - $8,535,360 (CI)

	Annual Quantity	Cost per Unit Quantity	Quantity per Ton of Product	$ per Ton of Product
VARIABLE COSTS				
Operating Labor (L)	48,000 man-hr	$ 7.00/man-hr	0.03	0.28
Supervision (S)	15% (L)			0.04
Labor Overhead	35% (L+S)			0.11
Maintenance (Labor & Materials)	-	-	-	0.41
Chemicals includes: • lime • chlorine • acid • activated carbon	-	-	-	0.28
Electrical Power	10,500,000 kWh	$ 0.016/kWh	8.77	0.14
Fuel	320,000 10^6 Btu	$ 2.00/10^6 Btu	0.266	0.53
TOTAL VARIABLE COST				1.79
FIXED COST				
Plant Overhead	65% (L+S)			0.21
Taxes & Insurance	2% CI	-	-	0.14
Depreciation 18 yrs	-	-	-	0.40
TOTAL FIXED COST	-	-	-	0.75
TOTAL ANNUAL COST	-	-	-	2.54
RETURN ON INVESTMENT	20% CI	-	-	1.42
TOTAL				$3.96/ton sponge iron or $2.77/ton steel

NOTES: 1) Cost estimates are for the ground-up implementation of the "Best Available Technology Economically Achievable" treatment level (1983).

2) Cost does not include wastewater treatment sludge disposal.

TABLE IV-32

DIRECT REDUCTION VS BASE CASE COMPARISON OF WASTEWATER TREATMENT COSTS

($/ton of Product)

	BASE CASE	DIRECT REDUCTION
VARIABLE COSTS		
Operating Labor (L)	0.49	0.28
Supervision (S)	0.07	0.04
Labor Overhead	0.20	0.11
Maintenance (Labor & Materials)	0.71	0.41
Chemicals includes: • lime • chlorine • acid • activated carbon	0.26	0.28
Electrical Power	0.17	0.14
Fuel	0.72	0.53
TOTAL VARIABLE COST	2.68	1.79
FIXED COST		
Taxes & Insurance	0.31	0.14
Depreciation	0.87	0.40
TOTAL FIXED COST	1.54	0.75
TOTAL ANNUAL COST	4.22	2.54
RETURN ON INVESTMENT	3.12	1.42
TOTAL	$7.34/ton hot metal $5.15/ton steel	$3.96/ton sponge iron or $2.77/ton steel

NOTES:
1) Cost estimates are for the ground-up implementation of the "Best Available Technology Economically Achievable" treatment level (1983).
2) Costs do not include wastewater treatment sludge disposal.
3) Both routes use about 30% scrap in the steelmaking step.

(2) Direct Reduction

The direct-reduction process produces four sources of solid waste:

- Direct reduction kiln waste,
- Wastewater treatment sludge,
- Electric furnace slag, and
- Electric furnace air pollution control dust.

The direct reduction kiln waste consists of the following components:

- lime - 140 lb/ton of output
- coal ash - 125 lb/ton of output
- discarded coal* - 100 lb/ton of output

Total solid waste = 365 lb/ton of output

This is equivalent to 219,600 ton/yr from a 1,200,000-ton/yr direct-reduction facility.

Wastewater treatment sludge is estimated to be generated at a rate of 187,000 ton/yr of dewatered sludge (@ 35% solids). The wastewater treatment sludge should be similar to blast furnace scrubber water sludge in that the liquid fraction of the sludge will probably contain cyanide, ammonia, phenol, and sulfide. However, there should not be any fluoride present in the wastewater treatment sludge from the direct-reduction alternative. As in the case of the blast furnace wastewater treatment sludge, care must be taken in its disposal to avoid groundwater contamination.

Electric furnace slag is estimated to be generated at the rate of 239,400 ton/yr, and electric furnace air pollution control dust is estimated at 8,600 ton/yr. In a qualitative sense, the environmental problems associated with the disposal of solid waste from the direct-reduction process are very nearly the same as those associated with the conventional base case operations. An estimation of the total yearly solid waste disposal cost for the direct reduction process is:

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*A major part of the larger sized coal particles can be separated from the ash and recycled. Coal fines that cannot be screened from the ash are discarded.

Waste Stream	Yearly Quantity (ton/yr)	Total Yearly Disposal Cost[1] ($/yr)	Unit Disposal Cost ($/ton of steel)
Kiln Waste	219,600	1,098,000	0.64
Wastewater Treatment Sludge	187,800	939,000	0.55
Electric Furnace Slag	252,000	1,260,000	0.74
Electric Furnace Dust[2]	9,000	45,000	0.03
TOTAL SOLID WASTE	668,400	3,342,000	$1.96/ton steel

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(1) Disposal cost @ $5.00 per actual ton

(2) The air pollution control for the arc furnace is a bag house.

While it is not considered in detail here, we understand that fines may be generated by abrasion of the iron oxide pellets in the direct-reduction units leading to iron losses. If a direct-reduction unit were in an integrated steel plant having a sinter strand, such fines could be fed to this unit. Alternatively, a limited amount of fines could be fed into the electric arc furnaces. However, if a significant quantity of fines were generated in a non-integrated plant, it may cause a pollution problem, either of dusting to the atmosphere, or the fines being entrained in rain water run-off. Further research is needed to define the magnitude of this problem.

From these estimates it appears that the direct-reduction process has a slightly higher solid waste disposal cost. The quantities of solid wastes from the various operations included in this comparison can vary considerably from plant to plant. It is conceivable that in certain instances the direct-reduction process could generate the same or even less solid waste than the base case. On the whole, the solid waste disposal problems and cost for the two alternatives are very nearly the same and certainly not different enough in quantity, cost, or impact to serve as a deciding factor.

d. Summary of the Pollution Control Comparison

In conclusion to the preceding paragraphs:

- The direct-reduction route creates less severe pollution problems, as the coke plant weighs heavily in the total amount of pollutants generated in the base case.
- Consequently, pollution control costs are significantly lower with the direct-reduction route. Capital costs are reduced by one-third ($20 million versus $30 million) and operating costs are 15% lower ($7.94 versus $9.26 per ton of steel); see Table IV-33.

TABLE IV-33

SUMMARY OF POLLUTION CONTROL COSTS

	Base Line	Direct Reduction Route
Capital Costs:		
Air	$11,080,000	11,258,000
Water	$18,700,000	8,535,360
Solid	-	-
Total	$29,780,000	$19,793,360
Operating Costs ($/ton of steel)		
Air	2.62	3.21
Water	5.15	2.77
Solid	1.49	1.96
Total	$9.26	$7.94

3. Energy Usage

Table IV-34 summarizes the energy usage of the conventional and direct-reduction routes for making steel. Clearly the direct-reduction route uses more energy (18.45 Btu/ton) than the conventional route (11.84 Btu/ton).* The base line has the advantage that the blast furnace is a remarkably efficient device against which several smaller direct-reduction vessels have a net thermal disadvantage. This is aggravated by the fact that the pellets must be substantially (if not completely) cooled before being transferred to the electric furnace.

As noted earlier the exhaust gases from the kiln may represent a heating value of 70 Btu/scf. This, however, can vary with time and is subject to various operating parameters. Since the gases have a low heating value we believe it would be difficult to use them economically and thus no energy credit is taken in this analysis. The energy advantage of the direct reduction is its ability to use non-coking coal, a resource that is much more plentiful and cheaper than metallurgical coal.

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*These numbers do not include the power consumption of ancillary equipment such as handling, etc.

TABLE IV-34

ENERGY REQUIREMENTS OF THE CONVENTIONAL AND DIRECT REDUCTION STEELMAKING ROUTES

	10^6 Btu/ton steel	
Direct Reduction		
Kiln		
Coal	10.96	
Electric Power(1)	0.41	
Electric Arc Furnace		
Electric Power(1)	6.30	
Total Production		17.67
Pollution Controls:		
Air: Kiln (electric power)	0.036	
EAF (electric power)	0.487	
Water: Kiln (electric power)	0.065	
Kiln (fuel)	0.187	
Total Pollution		0.78
Total:		18.45
Base Line		
Coke Oven	1.85	
Blast Furnace	9.45	
Basic Oxygen Process(2)	(0.13)	
Total Production		11.17
Pollution Controls:		
Air (electric power)(1)	0.34	
Water (electric power)(1)	0.08	
Water (fuel)	0.25	
Total Pollution		0.67
Total:		11.84

(1) 1 kWh = 10,500 Btu fuel equivalent at power source.
(2) Includes 0.44×10^6 Btu credit for CO recovery.

Remark: This table assumes that both the base case and the direct reduction alternative use 30% scrap with a zero energy content.

4. Investments and Operating Costs

a. Capital Costs

The same production capacities were adopted for comparing the base line and the option. Table IV-35 summarizes the capital costs of the two routes.

Modern direct-reduction facilities often consist of one or several 400,000 ton/yr modules. One such SL/RN facility includes the raw materials intake and the handling facilities for the shipment of products. The economy of scale realized with three kilns is small and rests largely with the raw materials and products handling capacity. A direct-reduction plant, including three SL/RN kilns, was estimated to cost about $168 million. The electric arc furnace shop has a capacity for melting 30% scrap and 70% prereduced materials. Its capital cost is $65 million, bringing the total capital associated with the production costs to $233 million. For comparison the base line investments are estimated to be $195 million. Due to the absence of the coke oven and the simpler pollution technology required by electric furnaces (as compared to BOP's), the cost of pollution of the DR route is 2/3 that of the base line ($20 million versus $30 million).

TABLE IV-35

CAPITAL COSTS

BASE CASE:			
Process Unit	Capacity (ton/yr)	Investment ($$10^6$)	
Coke Oven	660,000 (coke)	60	
Blast Furnace	1,200,000 (iron)	90	
BOF Shop	1,710,000 (steel)	45	
Total Production			195
Wastewater Treatment		18.70	
Air Pollution Control		11.08	
Total Pollution			29.78
TOTAL BASE CASE			$224.78
DIRECT REDUCTION:			
Process Unit	Capacity (ton/yr)	Capital ($$10^6$)	
Three Kilns	1,200,000 (iron)	168	
Kiln Air Treatment			
EAF Shop	1,710,000 (steel)	65	
Total Production			233
Wastewater Treatment		8.53	
Air Pollution Control		11.26	
Total Pollution			19.79
TOTAL DIRECT REDUCTION			$252.79

The total capital costs of the DR route are $253 million, or 10% more than that of the base case ($225 million). Such a difference is well within the cost estimating procedure; thus both routes can be considered equally capital-intensive. From the viewpoint of minimizing investments, much larger facilities would favor the blast furnace route, because of the economy of scale. Conversely, much smaller facilities would favor the direct-reduction approach.

b. Operating Costs

Tables IV-36 through IV-38 give the breakdown of the operating costs of the three process units of the base line sequence. The pollution control costs are excluded, as they have been reported separately. On this basis, raw steel costs $134.14/ton. The pollution control costs are $9.26/ton, so that the total charge against raw steel production is $143.40/ton.

Tables IV-39 and IV-40 give the breakdown of the operating costs of the two process units of the DR route: raw steel costs $139.89 a ton. Lower pollution costs still add $7.94, giving a total charge against raw steel production of $147.83.

The 3% difference between the two routes shown in Table IV-41 is well within the cost estimate uncertainty and does not favor either route. Operating costs again do not constitute a significant decision factor.

5. Adoption Status

Table IV-42 gives the nominal characteristics of existing SL/RN facilities around the world as communicated by Lurgi (1975).

The SL/RN process has had a history of operating difficulties. While some of our industry contacts clearly question whether these technical problems can ever be solved with a kiln based process, others are more optimistic. Construction of an SL/RN kiln 19.7 ft in diameter and 410 ft long has just been completed at Griffith Mine in Northern Ontario. It has a design capacity of 400,000 net tons of prereduced pellets per year. The solid reductant is a subbituminous coal from Alberta; the prereduced pellets (95% Fe) will possibly be shipped, by the same rail cars bringing the coal, to a 500,000-ton/yr steel mill in Alberta featuring three electric furnaces. Any objectionable (more than 1%) reoxidation of the pellets during transportation is expected to be effectively prevented by use of covered railroad cars. The degree of success with which this facility will operate will be closely watched by the iron and steel industry as a new test of the viability of the process.

The results of this new plant cannot be judged before a few years of successful operation have passed. Moreover, the success of such a plant is closely related to its feed material and is, therefore, site specific. Given the historical experience of similar operations in the past, we do not expect the steel industry to adopt this process extensively in the near-term future. Successful testing of the Griffith Mine facility would go far in alleviating the concerns about the technical viability of a coal-based rotary kiln process.

TABLE IV-36

COST STRUCTURE IN NEW COKE-MAKING FACILITIES

Annual Design Capacity: 660,000
Capital Investment: $60 million
Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/ton of Product
VARIABLE COSTS				
Raw Materials				
• metallurgical coal	ton	50.00	1.43	71.43
Byproduct Credits				
• ammonium sulfate	ton	94.00	0.02	(1.88)
Energy				
• Purchased Steam	1000 lb	3.00	0.67	2.01
• Electric Power Purchased	kWh	0.016	25.00	0.40
Energy Credits (Specify form)				
• coke oven gas	10^6 Btu	2.00	4.5	(9.00)
• BTX	gal	0.70	3.0	(2.10)
• tar	gal	0.43	10	(4.30)
• coke breeze	ton	40.00	0.05	(2.00)
Water				
• Cooling (Circulating rate)		0.05	5	0.25
Direct Operating Labor (Wages)	man-hr	7.00	0.25	1.75
Direct Supervisory Wages	15% labor			0.26
Maintenance Labor and materials	6% CI			5.45
Labor Overhead	35% (L&S)			0.70
• Operating supplies				1.00
TOTAL VARIABLE COSTS				67.97
FIXED COSTS				
Plant Overhead	65% (L&S)			1.31
Local Taxes and Insurance	2% CI			1.82
Depreciation 18 years				5.00
TOTAL PRODUCTION COSTS				72.10
Return on Investment (pretax)	20% CI			18.18
TOTAL				90.28

TABLE IV-37

COST STRUCTURE IN NEW BLAST FURNACE FACILITIES

Annual Design Capacity: 1.22×10^6 tons hot metal

Capital Investment: $90 million

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials				
• Pellets	Btu	0.45	84.7	38.11
• limestone	ton	5.00	0.25	1.25
Energy (Details on Table B)				
• Purchased coke	ton	90.25	0.53	47.85
• Electric Power Purchased	kWh	0.016	25.00	0.40
Energy Credits (Specify form)				
• blast furnace	10^6 Btu	2.0	3.8	(7.60)
Water				
• Cooling (Circulating rate)	10^3 gal	0.05	11	0.55
Labor (Wages) (1)	man-hr	7.00	0.15	1.05
Direct Supervisory Wages (s)	15% labor			0.16
Maintenance Labor and Material	5% CI			3.69
Labor Overhead	35% (L&S)			0.42
Misc. Variable Costs/Credits(a)				
• slag sampling				0.25
• scrap credit	ton	80.00	0.01	(0.80)
TOTAL VARIABLE COSTS				85.33
FIXED COSTS				
Plant Overhead	65% (L&S)			0.79
Local Taxes and Insurance	2% CI			1.48
Depreciation 18 years				4.06
TOTAL PRODUCTION COSTS				86.21
Return on Investment (pretax)	20% CI			14.76
TOTAL				106.42

TABLE IV-38

COST STRUCTURE IN NEW BASIC OXYGEN PROCESS

Annual Design Capacity: 1.71 million tons steel

Capital Investment: $45 million

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials				
• Hot Metal (93% Fe)	ton	106.42	0.83	88.33
• Scrap (96% Fe)	ton	80.00	0.35	28
Energy				
• Electric Power Purchased	kWh	0.016	30	0.48
Energy Credits (Specify term)				
• Carbon monoxide	10^6 Btu	2.00	0.44	(.88)
Water				
• Cooling (Circulating rate)	1000 gal	0.05	2	0.10
Direct Operating Labor (Wages)	man-hr	7	0.25	1.75
Direct Supervisory Wages	15% labor			0.26
Maintenance Labor and materials	8% CI			2.09
Labor Overhead	35% (L&S)			0.70
Misc. Variable Costs/Credits				
• oxygen	ton	10	0.08	0.80
• FeMn, lime, spar				3.00
• Slag disposal, hot metal, scrap treatment				1.00
TOTAL VARIABLE COSTS				125.63
FIXED COSTS				
Plant Overhead	65% (L&S)			1.31
Local Taxes and Insurance	2% CI			0.52
Depreciation 18 years				1.45
TOTAL PRODUCTION COSTS				128.90
Return on Investment (pretax)	20% CI			5.23
TOTAL				134.14

TABLE IV-39

COST STRUCTURE IN NEW SPONGE IRON (93% METALLIZED) FACILITIES

Annaul Design Capacity: 1,200,000 tons

Capital Investment: $\$168 \times 10^6$

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	\$/Unit	Units Consumed per Ton of Product	\$/Ton of Product
VARIABLE COSTS				
Raw Materials				
• pellets	Ltu	0.45	8.5	38.25
• limestone	ton	5.00	0.140	0.70
Energy (Details on Table B)				
• Purchased Fuel	10^6 Btu	2.00		
• Coal	ton	25.00	0.625	15.62
• Purchased Steam	10^6 Btu	3.00		
• Electric Power Purchased	kWh	0.018	56.0	0.90
• Misc.				
Water				
• Process (Consumption)	10^3 gal	0.50		
• Cooling (Circulating rate)	10^3 gal	0.05	4	0.20
Direct Operating Labor (Wages) (L)	man-hr	7.00	0.20	1.40
Direct Supervisory Wages (S)	L		15% L	0.21
Maintenance Materials and Supplies	4% CI			5.60
Labor Overhead	35% (L&S)			0.56
TOTAL VARIABLE COSTS				63.44
FIXED COSTS				
Plant Overhead	65% (L&S)			1.05
Local Taxes and Insurance	2% CI			2.80
Depreciation 18 years				7.84
TOTAL PRODUCTION COSTS				35.83
Return on Investment (pretax)	20% CI			28.00
TOTAL				102.88

TABLE IV-40

COST STRUCTURE IN NEW ELECTRIC FURNACE SHOP

Annual Design Capacity: 1.71×10^6 tons

Capital Investment: $65 million

Location: Great Lakes

	Units Used in Costing or Annual Cost Basis	$/Unit	Units Consumed per Ton of Product	$/Ton of Product
VARIABLE COSTS				
Raw Materials				
● reduced pellets	ton Fe	102.88	0.75	77.16
● scrap	ton	80	0.32	25.60
Energy				
● Electric Power Purchased	kWh	0.016	600	9.60
● electrodes	lb	0.55	10	5.50
Water				
● Process (Consumption)				
● Cooling (Circulating rate)				
Direct Operating Labor (Wages)	man-hr	7.00	0.3	2.10
Direct Supervisory Wages	15% Labor			0.32
Maintenance Labor and Materials	6% CI			2.27
Labor Overhead	35% (L&S)			0.85
Misc. Variable Costs/Credits				
● refractories				2.00
● fluxes, oxygen, misc. nonmetallics				1.00
● metallic additions				1.50
TOTAL VARIABLES COSTS				127.90
FIXED COSTS				
Plant Overhead	65% (L&S)			1.57
Local Taxes and Insurance	2% CI			0.76
Depreciation 18 years				2.10
TOTAL PRODUCTION COSTS				131.83
Return on Investment (pretax)	20% CI			7.56
TOTAL				139.89

TABLE IV-41

OPERATING COSTS
($/ton of steel)

	Base Case	Direct Reduction
Production Costs:	134.14	139.89
Pollution Costs:	9.26	7.94
GRAND TOTAL	$143.40	$147.83

TABLE IV-42

SL/RN PLANTS AND ROTARY KILNS FOR PREREDUCTION TO FEED ELECTRIC REDUCTION FURNACES (PLANTS BUILT OR UNDER CONSTRUCTION)

Company	Highveld Steel and Vanadium Corp. South Africa +	New Zealand Steel Ltd. New Zealand	Western Titanium Corporation Australia	Acos Finos Piratini Brazil	Nippon Kokan KK Fukuyama Japan	Hecla Mining Arizona USA	Steel Corp. of Canada Canada
Plant size	6 kilns 4 x 60 m kiln nos. 7/8 under construction start-up, late 1976	1 kiln 4 x 75 m	1 kiln 2.4 x 30 m	1 kiln 3.6 x 50 m	1 kiln 6 x 70 m with pre-hardening grate 250 sqm	1 kiln 3.6 x 50 m separate pellet indurating machine	1 kiln 6 x 125 m
Ore Throughput	2,000,000 mtpy	190,000 mtpy	20,000 mtpy	95,000 mtpy	325,000 mtpy	95,000 mtpy	520,000 mtpy
Raw Materials	Lump ore 1-25 mm	Iron sand concentrate	Ilmenite concentrate	lump ore, pellets	Bf, BOF-dust and Ore fines pellets	Leach-Residue pellets	Pellets
Ore	55% Fe 1.6% V_2O_5	58.0% Fe 8% TiO_2		67.0% Fe		50-53% Fe	66.5% Fe
Coal	high-volatile	sub-bituminous	bituminous	high-volatile	bituminous	sub-bituminous	sub-bituminous
Product and Further Processing	45% pre-reduced ore smelter PIG IRON VANADIUM SLAG	High-met. concentrate arc furnace STEEL	High-met. concentrate leaching ARTIFICAL RUTILE	High-met. ore, pellets arc furnace STEEL	High-met. pellets, Zn, Pb blast furnace PIG IRON	High-met. pellets copper cementation	High-met. pellets arc furnace STEEL
Remarks	No SL/RN process Lurgi designed and delivered the kilns				Start-up early 1975	Start-up mid 1975	Start-up mid 1975

Source: Lurgi, September 1975

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